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REPORT ON THE THIRD MARAGING STEEL PROJECT REVIEW

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TABLE OF CONTENTS

REPORT ON THE THIRD MARAGING STEEL PROJECT REVIEW

A. M. Hall*

INTRODUCTION

The third in a series of meetings to review the technical status of the high-nickel maraging steels was held on July 24 and 25, 1963, at the Biltmore Hotel in Dayton, Ohio. The first meeting took place at Wright-Patterson Air Force Base, Ohio, on May 14, 1962, while the second review was held at the Biltmore Hotel in Dayton, Ohio, on November 7 and 8, 1962. The intervals of time between reviews have been deliberately made rather short because the needs of the big booster programs have made it urgent to disseminate information on the maraging steels promptly, and because data on these steels are being generated so rapidly that frequent reviews are advisable to keep the information exchange problem within bounds.

As was the case with the first two meetings, this meeting was arranged by the Load Bearing Materials Section of the Applications Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division. Lt. R. M. Dunco was general chairman.

Again, the purpose of this review was to discuss the technical progress which has been made with the maraging steels, not only since the previous review but also in the sum total. In particular, the objective was to exchange technical information recently generated on the maraging steels and to evaluate the results forthcoming from the numerous investigations of these steels which are in progress. The ultimate objective was to determine the pertinent properties of these steels, to delineate the optimum techniques for processing and fabricating them, to define the important problems to be expected in using them, and to identify means to eliminate or circumvent these problems.

Major William Postelnek, Director, Materials Application Division, Aeronautical Systems Division, made the introductory presentation for the Third Maraging Steel Project Review. During the succeeding four sessions, which occupied two full days, 24 technical presentations were made by members of a number of Government agencies and facilities, industrial concerns and research organizations. Abstracts of the presentations are recorded in the Appendix to this memorandum. In the section immediately below, highlights and inferences of the presentations made during the review are reported.

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*Chief, Ferrous and High Alloy Metallurgy Division, Battelle Memorial Institute.

SUMMARY

General Status

It is clear from the presentations which were made that, so far as most of the people involved are concerned, the period of introductory experience with the 18 per cent nickel type of maraging steel has passed. Considerable knowledge of this type of steel has now been accumulated, and much of the work currently in progress is directed toward evaluating and attacking the key problems which must be faced when structures are built from these steels to meet extremely high standards of performance and reliability. A substantial effort is being aimed also at filling in voids which exist in the body of knowledge regarding these steels.

It is to be noted that attention is being directed primarily to the 18 per cent nickel type of maraging steel in preference to the 20 per cent nickel and 25 per cent nickel types. The 18 per cent nickel maraging steel is hardened by means of a much simpler heat-treating schedule and is considered to be superior in fracture toughness. Among the grades of 18 per cent nickel maraging steel, major emphasis is being placed on those which develop yield strengths in the range of 200,000 to 250,000 psi on being heat treated according to the usual procedure (anneal at 1500 F and age 3 to 6 hours at 900 F). This is especially the case when material in plate thicknesses is under consideration. For sheet, the interest also extends to steels capable of developing 280,000- to 300,000-psi yield strength. An effort is under way to determine the capability of the 18 per cent nickel type of steel, or modifications thereof, to meet hull plate requirements for deep-submergence submarines. Here, the interest covers steels with yield strengths ranging down to some 140,000 psi.

Fracture Toughness

It is fairly well established that the plane-strain fracture toughness of the 18 per cent nickel maraging steels varies in an inverse manner with the yield strength developed on full heat treatment. According to information presented at the meeting, which probably should be considered as preliminary, the fracture toughness seems to decline at a moderate rate as yield strength increases up to values in the range of 240,000 to 245,000 psi. With further increases in yield strength, the data indicate that the toughness drops rapidly. Thus, it appears that the plane-strain fracture toughness of such grades as the 18Ni(280) and 18Ni(300) steels is significantly lower than that of the grades spanned by the 18Ni(200) and 18Ni(250) steels, while these in turn have somewhat less fracture toughness than such steels as the 18Ni(140) and 18Ni(160) grades. Accordingly, special attention is being directed toward such grades as the 18Ni(225) and 18Ni(235) steels for applications involving relatively thick highly stressed sections which will demand an optimum combination of strength and fracture toughness. Those maraging steels which are capable of the highest strength come in for greater consideration in assemblies composed of sheet because in thinner structures the demands placed on fracture toughness are less stringent and the measurement of fracture toughness can be made with more confidence. As a consequence, greater advantage can be taken

of the ultrahigh strengths attainable in the 18 per cent nickel maraging steels in the thinner structures. Conversely, with the hull-steel application, considerable latitude as to yield strength is permissible but the toughness requirements are quite unique and severe and, perhaps, cannot be met readily by the higher strength maraging steels.

As a family, the 18 per cent nickel maraging steels have demonstrated considerably greater plane-strain fracture toughness than the quenched-and-tempered steels. Even weldments of these steels, which are considerably less tough than parent metal, show far greater plane-strain fracture toughness than is observed in the conventionally heat-treated steels at the same strength level. And, of course, weldments in quenched-and-tempered steels are less tough than the corresponding parent metal.

It is to be noted that the bulk of the direct data on critical flaw size, reported for these steels, have been obtained on sheet. Most of the data on plane-strain fracture toughness, which have been derived from tests of specimens containing notches that simulate severe defects likely to be encountered in practice, refer to sheet. All of the 18 per cent nickel maraging steel vessels which have been burst tested thus far have been thin walled. Thus, considerable information has been accumulated which permits reasonably confident evaluation of the behavior of these steels in the presence of severe stress-raising defects, when the metal is in the form of sheet.

However, when it comes to plate thicknesses, the situation is different. Only a relatively small number of tests have been made in which a simulated severe defect, i.e., a through-the-wall or part-through fatigue crack, has been used. The reasons are obvious: the required specimens are large and consume much material; they are expensive to prepare and test; and they require special testing equipment because of their great size. Therefore, investigators resort to various types of reduced size specimens, most of which are designed to measure plane-strain fracture toughness under conditions which hopefully meet the requirements for plane strain. The relationship between operating stress and critical flaw size is then calculated from the fracture-toughness value obtained. No burst tests of 18 per cent nickel maraging steel vessels, with walls of plate thickness, have been made to date. Hence, there is no direct information on the performance of these steels in practice in the form of plate. However, most investigators appear to be satisfied that the use of subsized specimens is permissible and that the behavior of these steels in relatively thick sections in the presence of severe defects can be estimated successfully by the indirect means of calculation from plane-strain fracture toughness values, even though the validating data are quite meager.

Welding

The presentations reflected the existence of an impressive effort on welding. The welding methods which have been under investigation include TIG, MIG, short arc, submerged arc, and electron beam. Considerable attention is being directed at filler-metal composition. A substantial amount of information is being accumulated on the mechanical properties and fracture toughness of welds and welded joints, both as aged directly after welding and as solution

annealed and aged after welding. It is clear that, from the procedural standpoint, the 18 per cent nickel maraging steels are quite readily weldable. The most universal success is being achieved with the TIG process, while many investigators also report satisfactory results with MIG. Less experience has been acquired with the other processes. In terms of tensile yield and tensile ultimate strengths, joint efficiencies of 90 to 95 per cent appear to be readily achieved. As to fracture toughness, the values being obtained for weld metal are markedly lower than those for unaffected parent metal. There appears to be disagreement regarding the fracture toughness of the various regions in the weld-heat-affected zone. Factors of geometry and size make it difficult to test the particular parts of this zone. However, this zone in general seems to possess a toughness somewhat intermediate between that of the weld metal and the unaffected parent metal. The content of the presentations made at the review indicated that efforts to improve the fracture toughness of welds and weldments are still in the exploratory stage. Some of the influential factors have been identified, while others are suspected.

Flaws and Inspection

The fracture toughness of welds appears to be a critical problem from at least two points of view. From one standpoint, it can be said that the weld should have the greatest fracture toughness of any part of a structure because it is here that the probability of the presence of severe flaws tends to be the highest. Unfortunately, welds -- and this applies to conventionally heat-treated steels just as much as to maraging steels -- generally exhibit considerably less fracture toughness than does unaffected parent metal. From another point of view, and with specific reference to the 18 per cent nickel maraging steels in the form of plate of 1/2 inch thickness or so, the critical flaw size corresponding to such operating stresses of interest as 200,000 psi and upwards seems to be in the order of 0.02 to 0.03 inch in depth. Flaws of such small size impose a severe burden on nondestructive-inspection procedures. Several presentations touched on inspection, but the subject came under no detailed discussion at the meeting. Therefore, it should be emphasized that, under the existing circumstances, the capability of inspection procedures is just as vital and just as limiting a factor in the design and construction of high-performance structures as is fracture toughness. This applies to the inspection of as-received materials, but it is especially critical in connection with assembled structures.

Banding

From the information presented it was evident that all plate stock of the 18 per cent nickel maraging steels is banded to a greater or lesser degree. The composition and structure of the bands have not yet been definitely determined. However, it seems clear that the phenomenon involves the alternation of layers of martensite and retained austenite, a condition stemming from chemical heterogeneity developed during the solidification of the ingot. The banding may possibly involve other constituents besides these two. The fracture toughness of the metal when cracks propagate parallel to the bands is considerably lower than in the other directions of the plate. This relatively low short-transverse fracture toughness is not a serious lack in many loading situations;

but at transitions and points where the section size changes, which involve stressing in the short-transverse direction, the decrease in fracture toughness arising from the banded structure is extremely important.

The banding in these steels has another aspect. Some instances of delamination of plate along the bands were reported. Such a tendency could invite severe problems in forming and fabricating.

In one of the presentations, a study of a means to remove the banding was reported. Heat treatment of plate at 2300 F for 16 hours essentially eliminated the heterogeneous structure. However, longitudinal notched tension test results indicated that the homogenized material was not as tough as the original banded plate. Careful examination revealed that other structural changes had occurred in the homogenized metal which probably accounted for the decrease in fracture toughness. This investigation certainly pointed up the complexity of the banding problem and emphasized that its solution will require considerable effort.

Mill Processing

Though it has not been documented in a quantitative sense, it is evident that the degree or severity of banding varies from plate to plate, heat to heat, and perhaps from one part to another within a single plate. This, in itself, suggests that the phenomenon is subject to control. But it also indicates that the details and specifics of the steps involved in manufacturing the mill products have a profound influence on the characteristics of the product. In this connection, data were presented which indicate that fracture toughness is more sensitive than smooth-bar tensile properties to variations in production operations. In particular, it was observed that sheet from two heats of closely similar chemical composition were widely different in fracture toughness at the same strength level. It was speculated that variation in finish hot rolling temperature may have been responsible for the difference.

Grain Size

One of the features of wrought metals and alloys which can usually be varied considerably in mill processing is grain size. It was of interest to note that some data were presented at the meeting which suggest that grain size may be an important variable requiring some degree of control. A pronounced effect on elongation and reduction of area was reported. In this connection, the possibility might be kept in mind that effects which seem to be due to grain-size variations are actually caused by some other factor that changes along with grain size.

Forming and Fabricating

Investigations of mechanical and other types of properties, of welding, and of heat treating response have been reported which involved

sheet, plate, bar stock, and forgings. In addition, a considerable amount of work has been done on forming and fabricating thin-walled vessels by various methods. And, it has been established that the 18 per cent nickel maraging steels are amenable to roll forming, shear spinning, lap-joint construction, helical wrapping, and many other fabrication processes. However, no information was presented on the forming characteristics of these steels in plate thicknesses. Needless to say, an important consideration here is the influence of banding and the extent to which delamination will occur and become troublesome.

Further Research and Development

In one of the presentations, it was reported that the 18Ni(300) grade is susceptible to hydrogen-induced delayed failure but is more resistant than low-alloy quenched-and-tempered steels. Baking is effective in removing hydrogen. In another presentation, it was shown that these steels exhibit some anisotropy with respect to Young's modulus; it is particularly evident in severely cold-worked sheet. In addition, data have been obtained on Poisson's ratio, on the strain-hardening exponent, on the effect of temperature on fracture toughness, on fatigue resistance, on stress-corrosion cracking, on nitriding, on the effect of long-time holding at elevated temperatures, on creep strength, and on cleaning and plating procedures.

In addition, programs are in progress to develop maraging steels specifically for elevated-temperature service, to adapt them to the requirements of hull plate for deep-submergence submarines, and to develop casting grades and the required foundry technology.

APPENDIX

ABSTRACTS OF PRESENTATIONS

TABLE OF CONTENTS

APPENDIX

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

INTRODUCTION

by

Major William Postelnek, Director,
Materials Application Division,
Aeronautical Systems Division

Major Postelnek indicated that, among the family of high-nickel maraging steels, the largest share of the attention was being directed toward the 18Ni(250) grade. This grade has high strength and attractive fracture toughness and is considered readily producible in a wide range of forms and sizes. However, in spite of these favorable characteristics, Major Postelnek posed the question of whether this steel, promising as it is, is actually adequate for large booster cases requiring materials of construction in plate thicknesses.

He pointed out that, in applying this steel to big boosters requiring the ultimate in reliability, numerous critical problems remain. The degree of reproducibility of mechanical properties and the extent of their sensitivity to variations in composition and in heat treatment are important questions. Welding-wire composition is a critical issue requiring clarification. Another item of great importance is the capability of current inspection methods to detect the important flaws in the structure. In this connection, the vital question is whether or not the material actually has sufficient plane-strain fracture toughness to tolerate undetectable flaws when used in the thicknesses required by the design.

There are numerous additional problems. Some do not have quite the immediacy at this time that others do, in terms of large booster applications. In this category, Major Postelnek placed stress-corrosion cracking and fatigue characteristics.

SESSION I - EVALUATION OF MARAGING STEEL WELDS

The Properties of Welded 18Ni-7Co-5Mo Plate

by Z. P. Saperstein and B. V. Whiteson,
Douglas Aircraft Company, Douglas Missiles and
Space Systems Division

This presentation described studies of the smooth-bar tensile properties of welds and welded joints made by a number of procedures, the fracture toughness of parent plate and weldments, the fracture surfaces and microstructure of weldments, and the capability of the steel to sustain high loads in hostile environments. The experimental material was 3/4-inch-thick plate from an air-melted heat of 18Ni(250) steel.

Most of the welds were made by the MIG process, though a limited study was made on electron-beam welding. Joint configurations included single- and double-J. In most of the work reported, the weld deposit contained either about 0.5 per cent titanium or 1.2 per cent titanium. In the former case, the filler wire contained 0.6 per cent titanium. In the latter case, the technique used in making the bulk of the weldments was to implant a titanium wire in a groove machined longitudinally at the bottom of the joint, and then weld over it with the filler wire of 0.6 per cent titanium content. The implanted wire melted and alloyed very uniformly into the weld deposit.

As aged 3 hours at 900 F, the 0.5 per cent titanium weld metal showed about 243,000 psi tensile strength, 232,000 psi yield strength, 20 per cent reduction of area, and 7 per cent elongation in 2 inches. The values for weld metal containing 1.2 per cent titanium, as aged 3 hours at 900 F, were about 252,000 psi tensile strength, 236,000 psi yield strength, 20 per cent reduction of area, and 6 per cent elongation in 2 inches. The 0.5 per cent titanium weld metal showed 2 to 3 per cent austenite after aging at 875 F, this value remaining constant for aging times up to 12 hours; at 925 F, the austenite content increased linearly with time to about 17 per cent after 12 hours of aging. In contrast, the weld metal containing 1.2 per cent titanium showed much more austenite at intermediate aging times but it decreased as aging was continued to 12 hours.

As to weldments, the authors reported that those containing 1.2 per cent titanium were less sensitive to variations in aging conditions than those with 0.5 per cent titanium, with respect to smooth-bar tensile properties. Such relative insensitivity is considered quite vital because, in practice, aging and reaging will occur and heating temperatures may not always be controllable to close limits. The 0.5 per cent titanium weldments failed in the center of the fusion zone, except for specimens aged 3 hours at 950 F. On the other hand, the 1.2 per cent titanium weldments failed in the weld-heat-affected zone of the parent metal.

The presentation also briefly described the work Douglas has done on fracture toughness. In burst tests of small single-girth welded ultra-high-strength steel vessels, they found that failure initiated in shallow cracks adjacent to, or in, the weld. Also, the results obtained on a shallow-fatigue-cracked sheet tension specimen could be correlated quantitatively with the burst-test results and thereby could provide a quantitative measure of the material's sensitivity to cracklike defects. They concluded that the results obtained from these shallow-crack tensile specimens could be employed in formulating criteria for design, processing, and inspection.

In the initial stages of their fracture toughness studies on 3/4-inch plate of 18 per cent nickel maraging steel, the Douglas personnel used a shallow-cracked full-thickness specimen 48 by 12 inches with gage dimensions of 4 inches by 12 inches. Because of the costs, handling difficulties and consumption of material associated with so large a specimen, they developed a small one measuring 8 by 1/2 by 1/8 inch. They consider such a specimen permissible because their investigations have indicated that, for "brittle" material, critical crack size is independent of specimen geometry. With this specimen, they have studied aging variables and have compared the fracture toughness of weldments and parent plate.

It was of interest to note that the critical crack depth for parent plate aged 3 hours at 900 F was about 0.11 inch, while for plate aged 12 hours at 900 F it was about 0.08 inch. For weldments with welds having 1.2 per cent titanium, aged 12 hours at 900 F after welding, the critical crack depth was some 0.03 inch. Weldments that were reannealed and then aged 12 hours at 900 F showed less fracture toughness, the critical crack depth being about 0.025 inch. Low-energy electron-beam weldments showed about the same fracture toughness as the high-energy two-pass MIG weldments just discussed.

The size of the dendrites in the welds seemed to decrease as the titanium content increased. Austenite was found in the welds, as were small angular particles of another phase. A phase believed to be reverted austenite was found in heat-affected zones.

Douglas' tests also indicate that the 18 per cent nickel maraging steels are comparatively resistant to delayed failure under high stress in various aqueous, saline, and acid environments. The implication is that these steels are quite resistant to stress-corrosion cracking.

<u>Electron-Beam Welding of One-Half Inch Thick Maraging Steel</u>
by W. D. Padian, A. Toy, and R. Robelotto,
North American Aviation, Inc., Los Angeles Division

North American Aviation's interest in electron-beam welding (EB) of the 18 per cent nickel maraging steels is focused to a large extent on motor cases too big for complete heat treatment after assembly. Electron-beam welding might be useful here. In previous research on precipitation-hardening stainless steels, EB-welded joints showed higher efficiency in the as-welded condition than TIG or MIG joints, especially in thick sections. The higher joint efficiencies were attributed to the restraint of the parent metal on the narrow uniform weld and heat-affected zones produced by the EB technique. Accordingly, it was reasoned that EB might show similar advantages in welding maraging steel plate, including minimizing overaging and austenite reversion in the heat-affected zones as well as loss of titanium.

Studies were made on 1/2-inch-thick 18Ni(250) steel plate and 1-inch-thick 18Ni(200) plate. The 18Ni(250) steel was aged 3 hours at 915 F, while the 18Ni(200) grade was aged 3 hours at 900 F before welding. Material was tested as welded and as reaged. The joints were carefully cleaned, square-butt joints. The 1/2-inch, 18Ni(250) plate was welded from one side with 150-kv accelerating voltage, 17 ma beam current, 17 inches per minute travel speed, and a beam diameter of 0.008 inch. A filler strip was tack welded on the back side of this joint to help control contour. The 1-inch 18Ni(200) plate was welded from both sides, using 150-kv accelerating voltage, 13 ma beam current, 10 inches per minute travel speed, and 0.010-inch beam diameter.

In terms of smooth-bar tensile yield and tensile ultimate strength, joint efficiencies of 75 to 80 per cent were obtained in the as-welded condition. On reaging, 100 per cent efficiency was obtained. However, in either the as-welded or the reaged conditions, the reduction of area and the elongation were less than in the unwelded parent metal.

Metallographic studies revealed four structurally different zones in addition to the unaffected parent metal: (1) an inner fusion zone of columnar grains whose axis was parallel to the direction of the weld, (2) an outer fusion zone of columnar grains perpendicular to the direction of welding, (3) an inner heat-affected zone consisting of new martensite, and (4) an outer heat-affected zone showing banding and dark-etching segregates. X-ray diffraction studies indicated that all zones, except the outer heat-affected zone, were largely martensitic with only traces of austenite. The outer heat-affected zone contained 25 to 29 per cent austenite. The presence of this austenite did not appear to affect the tensile properties of the joint. The authors speculated that reduction in ductility may possibly be ascribable to the preferentially oriented columnar grains in the fusion zones.

Influence of Hydrogen on Delayed Failure of Maraging Steel
by A. R. Troiano,
Case Institute of Technology

This presentation was in the nature of a progress report on research under way to investigate the susceptibility of the 18 per cent nickel type of maraging steel to hydrogen-induced delayed failure. The investigation was directed to the 18Ni(300) grade. The samples used were reported to have a notched-to-unnotched tensile-strength ratio of 1.4 at 290,000 psi yield strength after a 1-hour anneal at 1500 F followed by aging 3 hours at 900 F. No retained austenite was found in the specimens; thus, this phase was not available to act as a sink for hydrogen.

The charging solution was 4 per cent H_2SO_4 poisoned with NaCN. In one series of experiments, specimens were charged various times at a current density of 0.02 amp per square inch. The effect was measured in terms of reduction of area. For the maraging steel, little loss of ductility occurred after 8 minutes of charging time; on the other hand, AISI 4340 heat treated to a comparable strength level (270,000 psi) became thoroughly brittle in 1 minute. It took 2 hours' charging time to reduce the ductility of the maraging steel from an original 52 per cent reduction of area to 20 per cent.

In another group of experiments, the influence on ductility produced by baking time at 300 F was studied. Several different charging conditions were used. The data indicated that the ductility of the maraging steel was restored after baking for much shorter times than those required for AISI 4340 samples. The latter required times in the order of 20 hours, while the ductility of the maraging steel was restored in from a few minutes to 1 hour. A cyclic charging schedule involving a current density of 0.07 amp per square inch and a total time of 21 hours built the hydrogen content of the maraging steel up to 6.7 ppm. Baking at 300 F for 7 hours reduced the hydrogen content to 1.7 ppm.

Other experiments on sharp notched specimens gave indications of the capability of the 18Ni(300) steel to resist hydrogen embrittlement under conditions of sustained loading. The root radius of the notch was 0.002 inch. It was concluded that the 18Ni(300) grade of maraging steel can be embrittled by hydrogen, but it is much more tolerant of this element than are the low-alloy hardenable steels at comparable strength levels.

Evaluation of High-Nickel Maraging Steel for Application in Large Booster Motor Fabrication
by P. P. Crimmins,
Aerojet-General Corporation, Solid Rocket Plant

A program is under way at Aerojet-General to investigate the smooth-bar tensile properties and aging response, the fracture toughness, the welding characteristics, and the mechanical properties of weldments, of various grades of 18 per cent nickel maraging steel in the form of 1/2-inch-thick plate. The data reported were obtained on seven heats of steel from six suppliers and included air melts, vacuum-degassed air melts, and consumable-electrode vacuum-arc remelts. The grades of steel were 18Ni(200), 18Ni(225), 18Ni(250), and 18Ni(300).

Studies were made of material as hot rolled and aged and as hot rolled, annealed 30 minutes at 1500 F, and aged. The temperatures used for aging were 850, 900, and 950 F; the aging times ranged up to 16 hours. At 950 F, overaging tended to occur after 4 hours, while at 850 F strength was generally increasing at 16 hours. Yield and ultimate strengths varied to a greater degree, as a function of aging conditions, than did ductility. Strengths in the transverse direction were generally 6,000 to 15,000 psi higher than in the longitudinal direction. The effects of aging time, aging temperature, and test direction were similar whether the material was aged as hot rolled or aged as annealed. However, the annealed and aged material was 10,000 to 15,000 psi stronger than the hot rolled and aged specimens. The ductilities were about the same.

Aerojet considers that the results emphasize the importance of controlling aging conditions. Depending on the actual cycle used, it is possible to obtain a 20,000 psi variation in yield strength with a 50 F variance in aging temperature (a fluctuation which would not be uncommon in a large furnace). Their data suggest that 900 F for 4 to 8 hours is the most satisfactory compromise aging schedule.

Limited studies were made on 4-inch-square bar stock of 18Ni(225) and 18Ni(300) grade steel. With respect to strength, the aging response of this material was about the same as that of plate. However, the ductility was significantly lower in the short transverse and transverse directions in comparison with either the longitudinal direction of the bar or of plate of comparable strength.

An effort was made to correlate the contents of cobalt, molybdenum, and titanium with the 0.2 per cent offset yield strength to be expected on aging with Aerojet's preferred cycle. The results of the multiple-regression analysis which was performed were expressed in the following equation:

$$\text{Yield strength (1000 psi)} = 15.1 + 9.1\ (\%\text{Co}) + 28.3\ (\%\text{Mo}) + 80.1\ (\%\text{Ti}).$$

It is reported that this equation shows that a 35,000-psi yield strength range is obtainable from heats produced within the specification limits for cobalt, molybdenum, and titanium. This finding emphasizes the need to conduct aging-response studies on each heat in order that heats and components with similar aging characteristics can be matched.

As to inclusion count, banding, laminations, segregation, grain size, and stringers of nonmetallics, Aerojet found little difference attributable to melting practice. They also found little difference among the various grades of maraging steel under study. Though the materials seem generally of acceptable quality, defects have been found in plate. In most instances these defects took the form of stringers of inclusions, alloy segregation, and laminations resulting from localized concentrations of inclusions. Again, the incidence of these defects in plate could not be correlated with melting practice. Aerojet pointed out that the finding of such defects emphasizes the need to thoroughly qualify material to be used in rocket-motor components.

Fracture toughness studies were made on fully aged plate with the notched slow-bend test, the shallow-crack tension test, the through-crack tension test, and the precracked impact test. The shallow-crack specimens were 28 by 1/2 by 4 inches. The through-crack specimens were 8 by 32 inches. Cracks were made by fatigue. The results obtained with the precracked impact specimens and the through-crack tension specimens indicated the same general toughness level for the material. Precracked impact tests, carried out at various temperatures between 400 F and -100 F, showed a steady decrease in W/A value without indications of a transition temperature.

Comparisons were made between the plane-strain fracture toughness values obtained with a shallow-notch full-size specimen, a subsize specimen (0.125 by 0.5 by 8 inches) with the notch in the surface, and a subsize specimen of the same dimensions with a through-the-thickness notch. Good agreement was obtained between the results from the subsize specimens notched in the surface and those from the full-size specimens. The results with the subsize specimen having the through-the-thickness notch were a little lower. The results obtained with a subsize notched slow-bend test (G_{NC} values) were slightly lower than those obtained with the subsize shallow-crack tension specimen (G_{IC} values). Again, when the notch was through the thickness the values tended to be lower than when the notch was in the surface.

Plane-strain fracture toughness tests were made on a variety of plate materials including vacuum degassed 18Ni(200) plate, air-melted 18Ni(225) plate and bar, 18Ni(250) plate, vacuum-arc remelted 18Ni(250) plate, and vacuum-arc remelted 18Ni(300) material. Taking all the fracture toughness data together (G_{NC} values) and considering them in terms of 0.2 per cent offset yield strength, it was observed that fracture toughness was quite high until yield strengths in the range of 240,000 to 245,000 psi were reached. Then the toughness dropped rapidly with further increase in yield strength.

Among welding processes, TIG has been investigated extensively, while MIG and the submerged-arc process have also been studied. With the TIG process, weld-deposit composition has been studied along with the mechanical properties of weldments and their metallurgical structure. Considerable loss of titanium content was found with the submerged-arc process. Also, it was easier to obtain a sound weld with TIG than with MIG.

Plane Strain Fracture Toughness Measurements of Solid Booster Case Materials
by H. E. Romine,
U. S. Naval Weapons Laboratory

In this program, a notched slow-bend test was planned to provide K_{Ic} fracture-toughness values for propagation of cracks either through the plate thickness or in the plane of the plate and for examining specific locations within a weld zone. The specimens were square bars with a breadth and depth equal to plate thickness and a length equal to about ten times plate thickness.

The test procedure was evaluated on two test panels of 18Ni(250) maraging steel 1/2-inch thick which were welded by the Curtiss-Wright Corporation. The welds were made by standard procedures. Tensile properties of the base material after heat treatment were reported to be 247,000 psi yield strength, 257,000 psi tensile strength, 11.5 per cent elongation, and 51 per cent reduction of area.

The two test panels were 12 inches wide by 18 inches long. The panels consisted of two halves welded in the middle along the 12-inch dimension. Panel A was designed to simulate a longitudinal seam weld in a large rocket casing and was aged 3 hours at 900 F after welding. Panel B was intended to simulate a girth weld, except that the entire panel was aged the second time, after welding, instead of aging only the weld zone. Thus, this panel was annealed, aged, welded, and reaged.

A fatigue crack produced by bending was used to form a natural starting crack at the root of the machined notch in the bend test bar. A few drops of water were placed in the notch to promote cracking at a lower stress level. After fatiguing, the notch area was carefully dried out. Development of the fatigue crack at the ends of the notch during stress cycling was observed by sighting through a 10X microscope and mirror arrangement. The aimed depth for a fatigue crack was 0.02 inch as viewed at the notch ends. The depths obtained ranged from 0.01 to 0.04 inch averaged across the notch width.

Tensile tests were made with a subsize specimen made by narrowing the test section on two sides while maintaining the full thickness of the plate. Double aging of parent metal in Panel B apparently raised the yield strength by 5,000 to 10,000 psi over single-aged Panel A. Elongation and reduction-of-area values across the welds probably were lowered in part by the presence of the beads acting as a reinforcement. Joint efficiencies of the welds were 92 and 94 per cent for tensile strength and 90 and 96 per cent for yield strength. The higher values were found in the Panel A weld with a single aging treatment of the base metal.

The average K_{Ic} fracture toughness values for parent metal in Panels A and B are listed below in 1000 psi $\sqrt{\text{in.}}$ units.

Panel	Notch Location	Stress Direction Relative to Final Rolling Direction Longitudinal	Transverse
A	Through the thickness	86	86
	Parallel to surface	91	93
B	Through the thickness	73	93
	Parallel to surface	86	93

Single-aged Panel A parent metal showed equal fracture-toughness values in the two directions of stress when fracture ran in the plane of the plate. The toughness was slightly greater when a crack parallel to the plate surface was being driven in the thickness direction of the plate. The double-aged Panel B parent metal had the lowest K_{Ic} value of 73,000 psi $\sqrt{in.}$ when through-thickness cracks were being driven in the plane of the plate perpendicular to the final rolling direction. It was surmised that the directional equality of fracture toughness resulting from cross rolling was not fully maintained after double aging.

A small shear lip was noted around the edge of the fracture surface in the 1/2-inch plate specimens; therefore, measured K_{Ic} values may be slightly higher than for true plane-strain fracture. If a K_{Ic} value of 90,000 psi $\sqrt{in.}$ is taken to be typical for cracks propagating through the plate thickness and operating stress is assumed to be 200,000 psi, the Irwin formula $K_{Ic} = 1.2\pi\sigma^2 a$ indicates that a surface crack about 0.05-inch deep would tend to initiate fracture in the parent metal.

By means of the slow-bend test, the K_{Ic} values for initiation of fracture from a fatigue crack at various locations in the weldments were determined. In the weld center, the K_{Ic} values were considerably lower than in the base metal for both directions of crack propagation. In the weld edge tests, the K_{Ic} value was a little less than base metal in one case and more in the other. Based on these limited tests, it was assumed that the lowest fracture toughness would be found in the center of the fusion zone and that the minimum K_{Ic} values probably are the governing factors for crack sensitivity in welds. If a K_{Ic} value of 50,000 psi $\sqrt{in.}$ is used for surface cracks propagating in the weld and operating stress across a longitudinal seam weld is assumed to be 200,000 psi, the Irwin formula indicates a surface crack depth tolerance of about 0.02 inch before fracture initiation in weld regions with the lowest toughness.

SESSION II - MECHANICAL PROPERTIES OF MARAGING STEELS

Evaluation of 18 Per Cent Ni-Co-Mo Maraging Steel for Heavy and Thin Wall Rocket Motor Case Applications

by G. R. Sippel and G. L. Vonnegut,
Allison Division, General Motors Corporation

The strength, fracture toughness, and other pertinent characteristics of 18 per cent nickel maraging steel parent material and TIG weldments were

determined for 0.400-inch plate, ring-rolled forgings, and 24-inch-diameter thin-wall (0.135-inch) roll-formed cylinders. The adequacy of inherent parent-material properties and suitability of roll forming and welding procedures for production of thin-wall rocket-motor cases was demonstrated by successful destructive hydrotests of two 24-inch-diameter subscale pressure vessels, each of which achieved 328,000 psi biaxial ultimate strength -- a 12.5 per cent improvement over the uniaxial ultimate strength of 290,000 psi.

The partial thickness fatigue-crack tensile (PTC) test was selected as the primary method for evaluating the fracture toughness of the rocket-motor-case materials. This test was chosen because it uses semielliptical precracks which extend only partially through the specimen thickness and thus quite closely simulate the type of defects most often found in motor cases. In addition, it was considered that the PTC test values give a more accurate indication of strength capability in terms of real defects in real hardware than can be obtained by any other known test.

The materials evaluated to date were 18Ni(300) steel in the form of 0.400-inch plate, a 0.400-inch-thick plate of 18Ni(270) steel, ring-rolled 24-inch diameter forgings of 18Ni(280) steel, and roll-formed 24-inch-diameter cylinders made from ring-rolled forgings. The materials were from consumable-electrode vacuum-arc-remelted metal. In evaluations of parent metal properties, the solution anneal used was 1 hour at 1500 F, while the aging treatment was 900 F for 3 hours.

The investigation of the two maraging steel plates covered fracture-toughness characteristics at two strength levels, anisotropy characteristics of typical mill plate products, and the strength, fracture toughness, and other pertinent characteristics of TIG welds using both 90° single-V- and 90° double-V-joint configurations. Prior to welding, the plate was solution annealed at 1500 F for 1 hour. The treatment after welding consisted of aging at 900 F for 3 hours. One parent plate exhibited an average uniaxial ultimate strength of 270,000 psi, while the other displayed a uniaxial ultimate strength of 300,000 psi. Uniaxial tensile joint efficiency was 95.6 per cent for the 90° single-V joint and 94.7 per cent for the 90° double-V joint. All tensile tests on weldments were made transverse to the weld line.

It was considered that the results of partial-thickness fatigue-crack tensile tests of the 0.400-inch plate indicated that both heats of plate possessed adequate fracture toughness. Both displayed notch tensile strength equal to or greater than the ultimate tensile strength in the presence of partial-thickness fatigue-crack defects up to approximately 0.0035 sq in. in area. This size is equivalent to a surfacing semielliptical crack approximately 0.100 inch long, which is regarded as the maximum that could be expected to escape detection by present rocket-motor-case inspection methods. The results also indicated that no significant anisotropy existed in either of these mill plate products with respect to fracture toughness.

Transverse notch strength in the presence of surfacing, crack-type defects located in various structural zones were determined for both the 90° single-V and 90° double-V type joints made in 0.400-inch-thick plate. The results indicated that the notch-strength joint efficiency, based on a semielliptical surfacing crack area of 0.005 sq in. (approximate crack length of 0.125 inch) in the weld deposit ranged from a low of 80 per cent for the

face side of the 90° single-V joint to a high of 93 per cent for the root side of this same joint. Parent-material fracture toughness was excellent. In both welds -- 90° single-V and 90 double-V joint -- fracture toughness in the "austenite reversion" portion of the heat-affected zones was equivalent to that of the parent material. Fracture toughness of the weld deposits was quite erratic and, on the average, was much less satisfactory than that of the parent material and "austenite reversion" band in the heat-affected zone.

On metallographic examination, one plate showed considerable banding and a fine grain size. The other plate exhibited a uniform, relatively coarse grain structure, due possibly to final reduction at a relatively high temperature. The structure was relatively free of banding. The authors considered that the difference in microstructure between these two chemically similar heats, along with the observed differences in their uniaxial tensile and fracture toughness properties, indicate that in addition to chemical composition the strength and fracture toughness of 18 per cent nickel maraging steels may be strongly influenced by melting and product-reduction practices.

Weld-heat-affected-zone microstructures appeared to be typical of those reported by other investigators, i.e., narrow, light-etching "1200° F austenite reversion" bands were clearly evident. Beyond each "reversion" band, where temperatures ranged below 1200° F, a darker etching overaged zone was present. As expected, the parent material adjacent to the fusion line exhibited grain growth resulting from exposure to temperatures approaching the melting point. Characteristic dendritic structures were observed in the weld deposit along with light-etching patches of a grain-boundary constituent (estimated 30 per cent) which was presumed to be austenite.

Several 24-inch-diameter by 0.135-inch-wall cylinders were roll formed by essentially the same three-pass 70 per cent reduction procedure used to produce D6ac cylinders. No processing difficulties were encountered. However, inspection of the first cylinder, made specifically to study the effects of roll-forming procedural variations, revealed a number of small ID surface tears and a network of "craze" cracks in several areas on the OD surface. Grinding the preforms minimized cracking, but the problem was not entirely eliminated.

The uniaxial tensile data for a typical ring-rolled forging conformed with the figures of 270,000-psi minimum 0.2 per cent yield and 280,000-psi minimum ultimate strength. Roll forming the annealed metal to 70 per cent reduction followed by re-solution treatment and aging at 900 F for 3 hours increased the yield and ultimate strengths by 15,000 psi and 10,000 psi, respectively. No anisotropy resulted from roll forming as evidenced by the equal strength values for specimens taken both axially and circumferentially from a typical roll-formed cylinder. Uniaxial tensile weld-joint efficiency averaged 92 per cent as compared with 95 per cent for welds in heavy plate described previously.

The fracture toughness of the ring-roll-forged and the roll-formed parent metal was judged to be adequate within the range of partial-thickness crack-type defects which might escape detection by current rocket-motor-case inspection procedures.

Data for TIG welds, made in a 0.180-inch-wall roll-formed cylinder indicated that notch-strength joint efficiency, based on a 0.005-square-inch semielliptical surfacing crack, located in the weld deposit on the root side of the joint, averaged 77 per cent. This value was slightly less than the lowest (80 per cent) value determined for weld deposits in plate joints wherein fracture toughness was quite variable. In view of the excellent 94 per cent notch strength efficiency of parent material in the presence of a 0.005-square-inch crack, the weld deposit value of 77 per cent was deemed rather discouraging and suggested that, unless methods are devised to improve weld-deposit fracture toughness, rocket-motor-case designers may need to compensate for this deficiency by providing heavier weld-joint-area reinforcements than anticipated on the basis of uniaxial properties alone. The data also indicated a need for additional studies to determine methods for improving the fracture toughness of cast weld deposits in 18 per cent nickel maraging steels. It was suggested that the most fruitful approach to this problem most likely involves variation of the filler-material composition. Other considerations are the basic welding process -- TIG, MIG, submerged arc, etc., and related procedural parameters -- and thermal and/or mechanical processing. Fracture toughness in an area midway between the weld deposit and the "austenite reversion" band was equivalent to that of parent material. As discussed previously, similar excellent behavior was noted for the "austenite reversion" band in plate welds.

Two pressure-vessel assemblies were fabricated and hydrotested. Each consisted of two roll-formed cylinders, 24 inches in diameter by 48 inches long and with a 0.130-inch wall, joined by a center circumferential weld.

The ring-rolled forgings were solution annealed at 1500 F for 1 hour and air cooled. The 0.5-inch-wall preforms, machined from ring-rolled forgings, were then roll formed at room temperature in three passes to a total reduction of 70 per cent. After roll forming, the cylinders were re-solution annealed at 1500 F for 1 hour and welded. The heat treatment after welding consisted of aging at 900 F for 3 hours.

Before pressurization to failure, each assembly was proof tested twice at a maximum pressure of 2570 psig (approximately 235,000-psi hoop stress) and inspected, and strain gages were applied at the midlength of each roll-formed cylinder. Subsequent pressurization to failure was achieved in approximately 70 seconds. The results of the destructive hydrotests based on PR/T calculations were as follows:

	Assembly S/N 1	Assembly S/N 2
Biaxial Proportional Limit, 1000 psi	292.8	299.2
Biaxial 0.2 Per Cent Yield Strength, 1000 psi	323.0	321.1
Biaxial Ultimate Strength, 1000 psi	327.5	328.0
Biaxial Ultimate Strength Improvement, per cent	11.1[a], 13.0[b]	13.5[a], 12.9[b]

(a) Based on uniaxial ultimate strength of laboratory cold-rolled (70 per cent) process-control specimens that accompanied each roll-formed cylinder through all phases of thermal treatment after roll forming.

(b) Based on axial specimens taken from assembly after hydrotest.

These values were considered representative of satisfactory material performance. The biaxial improvement achieved by each assembly closely approached the maximum predicted by theory for isotropic materials in a 2:1 biaxial stress environment.

In the destructive hydrotest considerable fragmentation occurred, although the failures appeared ductile as evidenced by the 100 per cent shear nature of the primary longitudinal fractures. Circumferential progression of branches off the primary fractures was of the "flat" variety. The authors reported that flat fracture progression in the circumferential direction has been observed in cylindrical pressure vessels fabricated from reliable lower strength-high fracture toughness steels and, therefore, does not indicate low fracture toughness in the assemblies made from the 18 per cent nickel maraging steels. However, the authors remark that the fragmentation of these assemblies at first seems incongruous in view of the excellent biaxial improvement, the 100 per cent shear nature of fracture, the excellent fracture toughness of rolled-formed cylinders, and the absence of fragmentation associated with failure of pressure vessels fabricated from other steels heat treated to high fracture-toughness levels. It is speculated that the difference in behavior may be related to the proximity of the 0.2 per cent yield and ultimate strength levels, and to the very high energy available to cause fracture progression. In D6ac steel, the 0.2 per cent yield and ultimate strengths may be separated by 15,000 to 25,000 psi, but with 18 per cent nickel maraging steel, the spread between these values was 3,000 to 6,000 psi. It was reported, also, that welds were in no way associated with fracture initiation.

<u>Evaluation of Maraging 18 Per Cent Nickel Steel Sheet and Plate Physical and Mechanical Properties and Some Fabrication Characteristics</u>
by G. K. Bhat and W. J. Persin, Mellon Institute

The fracture toughness of plate from three heats of 18 per cent nickel maraging steel was investigated. Plate thickness ranged from 0.415 to 0.665 inch, and the toughness indexes included G_c, K_c, and K_{Ic}. The types of test specimens used in the program were a center-slotted tension specimen, a partial-thickness fatigue-cracked tension specimen, and a precracked notch-bar bend test. In the course of the program, it was concluded that the test to obtain G_c was tedious and costly, and emphasis was switched to the use of the notch-bar bend test and the generation of K_c data. From the data they obtained from part-through-cracked specimens, the authors concluded that gross fracture stress began to decline at notch depths of about 20 per cent of section thickness for the thicker plate material and about 35 per cent for the thinner plate.

The influence of notch acuity and, hence, the size of the plastic zone around the notch, was investigated for sheet material at yield strength levels of 200,000, 240,000 and 258,000 psi. The thickness of the sheet was about 0.110 inch. Various types of specimens were used, and G_c, K_c, and K_{Ic} data were developed. Considerable variance in G_c values were observed. The K_{Ic} data obtained suggested to the authors that the strength level of the maraging steel may not determine its plane-strain fracture toughness. Also, they noted that the differences in K_{Ic} and G_c values obtained on specimens with machined notches and specimens with fatigue cracks were insignificant. From this they inferred that plastic-zone size may not play a dominant role, at least at yield strengths under about 240,000 psi.

The mechanical properties of a weldment prepared in 1-5/8-inch-thick plate by the TIG process were investigated. The weldment was a double-V butt joint made in 20 passes per side. After welding, the joint was aged 4 hours at 915 F. The yield strength of the parent plate was some 255,000 psi; and joint efficiencies were reported to be in the range of 86 per cent.

Finally, preliminary data were presented on another program concerned with the behavior of small thin-walled pressure vessels containing surface cracks of predetermined size inserted in the exterior wall perpendicular to the hoop direction by fatiguing. The program encompasses a number of ultrahigh-strength steels, including the 18Ni(250) and 18Ni(300) grades of maraging steel. The investigation is still in progress but, thus far, the performance of the nickel maraging steels has been outstanding.

Informal Summary on Welding of 18 Per Cent Nickel Maraging Steels
by R. E. Monroe, Battelle Memorial Institute

Based on the information which has thus far been generated in the numerous programs on the high-nickel maraging steels, the author identified points of general agreement and points of considerable disagreement among investigators, as they appeared to him. The following appeared to be the points of agreement:

(1) There is no problem in actually making TIG welds in maraging steels.

(2) The tensile properties of almost any kind of weld in maraging steel are acceptable on the basis of strength values. Joint efficiencies of from 90 to 95 per cent are readily obtainable by a number of welding processes.

(3) It is generally agreed that the fracture toughness of weld metal in maraging steel is poor in comparison with that of the parent metal.

(4) There is a significant amount of retained austenite in the weld metal of the maraging steels.

Those points where there seemed to be disagreement are as follows:

(1) Some investigators have encountered considerable porosity in MIG welds; others report none.

(2) Some investigators have rejected the submerged-arc welding process as not being suitable; others believe the process gives entirely adequate results.

(3) Sometimes high values are obtained for the fracture toughness of the heat-affected zones; sometimes the values are comparatively low.

(4) Opinions vary considerably as to the amount of titanium required in the filler wire to develop satisfactory strength and fracture toughness in the weld.

The following items were also mentioned, not necessarily as points of disagreement but to help clarify the presentations made during the meetings:

(1) It was pointed out that banding, which several investigators referred to as being quite pronounced in weld-heat-affected zones, was unrelated to welding. Welding thermal cycles merely make banding more prominent in these areas.

(2) Restraint in weldments was mentioned as a possible problem which does not appear to have been completely explored as yet.

(3) High hydrogen content in welds and cracking attributed thereto were also pointed out as items requiring more study, even though it is reported that hydrogen has very little effect on the maraging steels.

Finally, it was mentioned that more attention should be paid to the reporting of and the consideration of the variables in the welding processes. Among such items are voltage, amperage, travel speed, joint preparation, number of passes, gas, gas-flow rates, and filler-wire composition. More research should be done on the effect of such variables on the properties of the weldments, particularly fracture toughness.

<u>Helically Wrapped 18 Per Cent Nickel Maraging Steel Vessels</u>
by Walter Hauck, The Budd Company

As part of a long established program to develop the process of helical wrapping and butt welding of strip as a method of manufacture for rocket-motor cases, the adaptibility of an 18 per cent nickel maraging steel to fabrication by this process was investigated. The strip used was of the 18Ni(250) grade, 0.020 inch thick. A pressure vessel 6 inches OD by 42 inches long showed a biaxial gain of 11.3 per cent on being burst tested. Examination after test indicated that the welds had not been involved in the initiation of the fracture.

<u>Spin Forge Processing of the 300,000 psi Grade of Maraging 18 Per Cent Nickel Steel</u>
by R. P. Sernka, Lear Siegler, Inc.

The purpose of the work described here was evaluation of the response of the 300,000 psi grade of maraging steel to shear-spin processing and the effect of such processing on mechanical properties.

Three configurations of cylindrical chambers were shear spun. These were 11.7 inches in diameter and 56 inches long, 44 inches in diameter in multiple lengths, and 65 inches in diameter and 100 inches long. The steel was vacuum-arc remelted. In all instances, the starting condition was as solution annealed from 1500 F for 2 hours and air cooled. Grain size was in the range of ASTM 2.5 to 5. Microstructure was uniform except in one instance where severe banding was observed.

Initially, shear spinning was accomplished in an experimental program with the 44-inch-diameter cylinders, and most of the results reported here were from that program. Subsequently, semiproduction items have been produced in the other two diameters. Three of the 44-inch-diameter preforms were processed, two with starting wall thicknesses of 0.750 inch and the third with a 0.600-inch wall thickness. The first was arbitrarily designated No. 301 and the second and third designated No. 302 and No. 302A. Hardness of all preforms was 32 to 33 Rockwell C.

Cylinder No. 301 was spun in three passes to a nominal 0.142-inch wall thickness, utilizing a 120-inch-diameter machine which is capable of exerting a 140,000-lb roll pressure. Forming rollers were of the step type. Vertical feed rates of 3 to 4 inches per minute were utilized at 633 surface feet per minute. This sequence resulted in diametral growth of approximately 0.020 inch per pass in the 44-inch diameter. The full 76 per cent reduction was made without intermediate solution anneal. After spinning, Cylinder No. 301 was sectioned to obtain mechanical properties.

Cylinders Nos. 302 and 302A were processed in a manner similar to that of No. 301. The 0.750-inch wall thickness preform was spun to 0.245 inch (68 per cent reduction) without intermediate anneal. Three passes were employed, but with radius-type forming rollers where R = 0.750 inch. At thickness, reduction, and feed-rate levels comparable to No. 301, diameters were found to be 0.110 inch greater, indicating superior dimensional control with the higher unit forming pressures available from step-type rollers. Cylinder No. 302A was cut into two cylindrical sections after the 67 per cent reduction. The lower section, along with No. 302, was solution annealed at 1500 F for 1 hour. Cylinder No. 302 was spun in three more passes to 0.064-inch thickness, or 73 per cent reduction after heat treatment. An over-all 91.4 per cent reduction was obtained. No material defects were noted.

After sectioning, spinning operations on No. 302A were continued without benefit of solution anneal. A fourth pass to a 0.145-inch-thick wall and 81 per cent reduction was successfully made. However, a fifth pass to 86.5 per cent reduction resulted in fracture throughout the cylinder.

Based on the preliminary processing data described above, it was concluded that the 300,000 psi grade is readily adaptable to shear spinning and can be formed to approximately 82 per cent reduction without intermediate solution anneal.

The semiproduction 11.7- and 65-inch-diameter cylinders were spun to 87 per cent and 75 per cent total reductions, respectively. Since dimensional control was particularly important in the smaller diameter configurations, step-type forming rollers and feed rates up to 8 inches per minute were utilized on the first two passes. After intermediate solution treatment at 1500 F, spinning

was accomplished with 0.750-inch-radius rollers. The last spinning pass was performed by forward extrusion over 50 per cent of the part length until the part "bottomed out". The pass was completed by back extrusion. Such a procedure usually will cause thinning of the wall and a diametral bulge at the transition from forward to backward spinning. The maraging steel reacted only by a 0.002- to 0.003-inch step increase in wall thickness at the transition. This is attributed to the higher feed rates useable with the alloy and to its high yield strength.

The 65-inch-diameter cylinders were Minuteman first-stage configuration. The shear-spin sequence for these cylinders was similar to that used for No. 301.

A general conclusion obtained from shear spinning the 11.7- and 65-inch cylinders was that, for proper dimensional control, the 18 per cent nickel alloy's low work hardening rate requires a forming rate which is higher than most other steels. Hardness values of the maraging steel were observed to increase at a rate lower than that of other motor-case alloys.

Sample material from 44-inch-diameter cylinders was aged at 900 F for 2, 5, 8, 12, and 20 hours. Increases in tensile and yield strength of up to 30,000 psi, as compared with the annealed and aged forging, were obtained. Generally, tensile and yield strength reached a peak after about 8 hours' aging. Strength varied directly with amount of prior cold reduction. Samples representing 91.4 per cent total reduction with 73 per cent following an intermediate anneal exhibited the highest strength. This was attributed to grain refinement resulting from cold work prior to the intermediate solution anneal.

A second series of samples was solution treated at 1500 F and aged at 900, 950, and 1000 F for 3 hours. The samples represented both longitudinal and circumferential directions of the cylinder. Two reductions, 70 and 75 per cent, were considered. The results indicated that tensile elongation was increased by a factor of 2 to 3 over samples aged directly after forming. Strength was increased by 10,000 to 15,000 psi over that displayed by the forging. Properties indicated a slight directionality of about 5,000 to 7,000 psi. Strength was higher and ductility somewhat lower in the circumferential direction than in the longitudinal or axial direction.

Dimensional change in cylinders during intermediate or post-spinning heat treatment is of considerable importance to shear spin operation. Solution annealing after spinning produced a shrink in the work piece of 0.002 to 0.004 inch per inch of diameter. There also was a greater tendency toward a condition of ovality than normally exists with other motor-case alloys such as D6ac and AISI 4340 steel. However, the extent and position of the ovality did not seem consistent and, therefore, was not predictable.

Based on the results obtained to date from this program, the following conclusions were drawn regarding the shear spinning of the 18Ni(300) grade of maraging steel:

(1) The alloy is readily formed by shear spinning. For proper dimensional control, it requires feed rates approximately twice that used for other rocket-motor-case steels.

(2) Wall reductions of 80 to 82 per cent are possible without requiring a re-solution anneal. Fracture, along with a sharp rise in hardness, was observed at 86 per cent reduction.

(3) Cold work, performed by shear spinning before aging, causes a rise in tensile and yield strength of up to 30,000 psi.

(4) Solution treatment and aging after spinning results in an increase of 10,000 to 15,000 psi over properties obtainable in the forging.

(5) Solution treatment after spinning causes a diametral shrinkage of 0.002 to 0.004 inch per inch.

Evaluation of Potential Rocket Booster Motor Case Materials
by P. P. Puzak, U. S. Naval Research Laboratory

A program is in progress at NRL which is aimed at establishment of the potentialities and limitations of a variety of high-strength metals and alloys. A particular application toward which the investigation is aimed is hull plate for deep-submergence submarines. However, the data being generated are valuable in the evaluation of the materials for numerous other applications such as hydrofoils and rocket-motor cases. The program encompasses titanium alloys, aluminum alloys, quench-hardening low-alloy steels, and the high-nickel maraging steels.

The investigation covers many aspects of the technology of the test materials. Included are low-cycle fatigue, stress-corrosion cracking, corrosion fatigue, electron microfractography, in addition to smooth-bar tensile properties, drop-weight tear energy, and behavior in the explosion-bulge tear test. The purpose of such tests as the drop-weight tear and explosion-bulge tear tests, which measure fracture toughness, is to generate data with which to determine the limits of flaw size, strength, and temperature that result in failure. With this type of information, the designer hopefully can establish conditions such that, if failure does occur, it will be gradual rather than catastrophic.

The nickel maraging steels under study include some with yield strengths in the range of 140,000 to 160,000 psi, 200,000 psi, 230,000 psi, 250,000 psi, and 280,000 psi. Plate material 1 inch thick is used. Both air-melted and consumable-electrode vacuum-arc remelted material is included.

The drop-weight-tear (DWT) specimen is a bar 3 by 1 by 10 inches which is impact loaded in the middle as a free-end beam. The 1-inch dimension is the thickness of the plate material; NRL considers it important to test full thickness. Welded to the tension face of the DWT specimen is a brittle material which is notched in the middle; the purpose of this material is to act as a crack starter on impacting.

The results obtained to date with the DWT test indicate that the fracture toughness of the 18 per cent nickel maraging steels, in the form of 1-inch-thick plate, is comparable to that of the best specially prepared steels at the same yield-strength levels. At a yield-strength level of

140,000 to 160,000 psi, some of the consumable-electrode vacuum-arc-remelted maraging steel was superior. The DWT energy of maraging steels of 140,000 to 160,000 psi yield strength ranged from about 3000 to 7000 ft-lb. In the case of quenched-and-tempered steels, materials showing 3000 ft lb or more are expected to perform satisfactorily in the explosion bulge test. The energy level obtained for the 200,000 psi steels was about 1000 to 2000 ft-lb, while the higher strength grades showed 500 to 750 ft-lb energy.

The explosion-bulge test is performed on a specimen 22 by 25 by 1 inch which contains a 2-inch long intentional flaw in the center. To control the behavior of the material under the explosive force, the specimen is suitably drilled and slotted. The test is carried out with the metal at 30 F, the temperature of polar water. The 2-inch defect is considered to be a flaw of practical size from the standpoint of hull construction.

The maraging steels reported on tended to fracture, in the explosion-bulge tear test, without displaying much plastic deformation. The 140,000- to 160,000-psi steels showed a low-energy shear failure. The 18Ni (250) grade displayed almost no shearing and tended toward fragmentation. The 18Ni(280) grade shattered to a considerable extent. In the DWT test, the 160,000 psi steel showed a shear-type fracture, the 18Ni(250) grade showed very little evidence of shearing, and the 18Ni(280) steel had a completely square fracture.

The author emphasized the need for more information to correlate fracture toughness with other mechanical properties and with the independent variables, pointed out the necessity for evaluating the material in full thickness, called attention to NRL's experience that Charpy V-notch data do not discriminate as well as do DWT data, and gave the considered opinion that processing variables affect fracture toughness.

SESSION III - MECHANICAL PROPERTIES OF MARAGING STEELS

Metallurgical Evaluation of 18 Per Cent Nickel Maraging Steel (300,000 psi Strength Level)

by Al Melville, Wasatch Division, Thiokol Chemical Corporation

Metallurgical studies are being conducted to support the use of the 18 per cent nickel maraging steels at a strength level of 280,000 psi in an improved design of the First Stage Minuteman. The present Minuteman case material, D6ac, is used at a tensile ultimate strength of 225,000 psi. The higher strength of the 18 per cent nickel alloy would allow a weight reduction in the rocket-motor case because of the thinner case walls and thus would permit an increase in the range of the missile.

In conjunction with high strength, a high degree of notch toughness is required for rocket-motor cases. Accordingly, this investigation emphasizes the behavior of the 18 per cent nickel alloy at the 300,000-psi strength level in the presence of severe stress raisers, such as sharp radii, fabrication cracks, and microstructural discontinuities. The metallurgical areas investigated were:

(1) The effect of various maraging cycles on the tensile properties and fracture toughness (based on results of tests of center-notch and partial-thickness-crack specimens).

(2) The effect of short-time exposure in the temperature range of 1050 to 1350 F on the subsequent maraging response.

(3) Hydroburst results of 6-inch-diameter vessels to determine the biaxial behavior in a two-to-one stress field.

(4) Comparison with other structural materials.

Three heats of 18 per cent nickel maraging steel were used; two heats were in the form of 0.145-inch-thick sheet and the remaining heat was as a 0.250-inch plate. The chemical compositions of the heats were near the upper limit established for commercial 18 per cent nickel steel at the 300,000 psi strength level, with respect to cobalt, molybdenum, and titanium content. All three heats were vacuum-arc remelt material.

Aging characteristics were studied by using three types of mechanical test samples, i.e., flat tensile, center notch, and partial-thickness crack. The effect of maraging on the tensile and center-notch properties at temperatures of 850 F, 900 F, 950 F, and 1000 F for times up to 24 hours was investigated. The results obtained for the two heats which were in the form of 0.145-inch-thick sheet were quite divergent, even though the compositions of the two materials were closely similar. For given aging conditions, one of the heats showed consistently higher smooth-bar strength and fracture toughness. Frequently, the difference in strength was not great, but the difference in fracture toughness was significant. The aging response of the third heat (0.250-inch plate) was similar to that of the better of the other two heats.

When aging response was evaluated with tensile specimens containing part-through cracks, the results obtained paralleled those from through-notched specimens. The sheet material shown to be the better in the latter tests was also found to have high tolerance for part-through cracks; strength did not decline until the crack length reached about 0.240 inch. Strength dropped in the poorer sheet material at a crack length of 0.100 inch, while the tolerance limit for the 0.250-inch plate was a 0.225-inch crack. For all three materials, these crack-length values correspond to smooth-bar tensile ultimate strengths of approximately 300,000 psi.

The close agreement of tensile strengths for the three heats and the wide discrepancy in fracture-toughness results could not be explained. The difference did not seem to relate to chemical composition because of the similarity in analyses of the three heats. The possibility that a variation in finish hot-rolling temperature caused this difference in fracture toughness is presently being checked.

Comparison of the 18 per cent nickel maraging steel with other materials previously evaluated showed it to have a net strength-to-density ratio similar to that of Ardeformed 301 stainless steel at 300,000 psi and

heat treated Ti-6Al-4V alloy for partial crack lengths less than 0.100 inch. The poorest of the three maraging steels had notch properties which were equal to or in excess of the other materials for crack lengths up to 0.200 inch.

The aging response of the 18 per cent nickel steel was greatly reduced when the material was subjected to a short-time exposure at 1050 and 1250 F prior to maraging. The standard thermal treatment of 1500 F for 1 hour plus 900 F for 3 hours resulted in a hardness of 618 DPH. When the 900 F cycle was preceded by a 1250 F exposure for 10 minutes, the resulting hardness was 385 DPH. This poor aging response after exposure at 1050 to 1250 F could be completely eliminated by a subsequent 1500 F anneal. The maraging response showed a consistent decline with temperature increase over the range of 1050 to 1250 F, while the austenite content of the material showed a steady increase. A reversal in the hardness and austenite-content trend occurred when the exposure temperature was above 1250 F. The hardness obtained after exposure at 1300 to 1350 F was much greater than after exposure in the temperature range of 1050 to 1250 F, but never equaled that obtained after a 1500 F anneal.

Three 6-inch-diameter pressure vessels were hydrotested to failure. These were one-piece bottles finished to a wall thickness of 0.140 inch. The titanium content of the steel was comparatively high, viz., 1.04 per cent. The three bottles were annealed 1 hour at 1500 F, air cooled, aged 3 hours at 900 F, and air cooled. The anticipated biaxial upgrading of 15 per cent was not realized with the 18 per cent nickel steel vessels. The three tests gave a range of values from 5 per cent to 11 per cent. The biaxial hoop strength ranged from 330,000 to 350,000 psi. The failed bottles had the appearance of brittle failure because of severe fragmentation, but the cylinder walls possessed some ductility as indicated by the ductile shear lip on the fracture face.

Anisotropy of Young's Modulus in 18 Per Cent Nickel Maraging Steel

by Richard E. Lewis, Lockheed Missiles and Space Company

Widely differing values for Young's modulus have been reported by various investigators. At the ASD First Maraging Steel Project Review, May 14, 1962, values were reported from 16.5 to 27.5 x 10^6 psi. Very little scatter in modulus was reported at the Second Maraging Steel Project Review, November 7-8, 1962. Values reported were 27 x 10^6 psi for aged material and "somewhat less" for annealed material.

Concern over potentially significant variations in modulus which might influence critical design applications of the material prompted LMSC to determine the maximum variations produced by possible process conditions, and to explore causes of these variations. Process conditions selected were aging time and temperature, cold working, re-solution annealing, and combinations of these. Modulus was measured for various orientations from the final rolling direction to disclose modulus anisotropy, if present.

Investigations of possible causes of observed differences in moduli and degree of anisotropy in modulus have not been completed, and so are not discussed in this report.

The material used in the program was a 24 by 72 by 1/8-inch sheet of the 18Ni(250) grade of maraging steel which had been produced from a consumable-electrode vacuum-arc-remelted ingot. When annealed at 1500 F and aged 3 hours at 900 F, transverse specimens had tensile strengths in the range of 277,000 to 279,000 psi, 0.2 per cent offset yield strengths of 250,000 to 264,000 psi, and elongations in 1 inch of 4.5 to 5.5 per cent.

The sheet supplied by the mill was solution annealed only. All subsequent heat treatment was performed by LMSC. Pieces approximately 6 by 12 inches were cut from the as-received sheet. Some of these pieces had modulus specimens extracted from them directly; most of the pieces were used for subsequent heat treatment or cold rolling or both, before specimens were extracted. The pieces were cold rolled in the same direction as the final hot rolling. Reduction per pass was 1/2 per cent to 5 per cent of thickness, depending on total reduction required. Young's modulus was determined by the dynamic method, using reed-type specimens.

A series of specimens was first prepared to survey widely varying process-history conditions that might cause maximum change in elastic modulus. Specimens both parallel and perpendicular to the principal rolling direction were obtained. The seven conditions examined were as follows:

(1) As-received (solution annealed 15 minutes at 1500 F)

(2) Aged 3 hours at 900 F

(3) Cold worked 60 per cent

(4) Cold worked 60 per cent and aged 3 hours at 900 F

(5) Cold worked 60 per cent, re-solution annealed 1 hour at 1500 F, and aged 3 hours at 900 F

(6) Re-solution annealed 1 hour at 1500 F

(7) Re-solution annealed 1 hour at 1500 F, cold worked 60 per cent, and aged 3 hours at 900 F.

Two process sequences of practical significance were then examined in detail: (1) cold worked plus aged and (2) cold worked plus re-solution annealed plus aged. Cold-working reductions of 0, 2, 10, and 60 per cent were incorporated. Aging conditions were 800, 900, and 1000 F for 1/2, 1-1/2, and 3 hours. Young's modulus was obtained for the 0, 45, 60, and 90-degree orientations from the principal rolling direction.

The conclusions drawn from the results obtained to date were as follows:

(1) Anisotropy in Young's modulus exists in this material for all conditions studied. In the annealed condition, typical moduli are 25.8 and 27.6 x 10^6 psi, parallel and perpendicular, respectively, to the principal rolling direction.

(2) Either aging or re-solution treating plus aging raises the moduli 1 to 2 x 10^6 psi. Variations in aging time from 1/2 to 3 hours at temperatures from 800 to 1000 F do not produce any significant difference.

(3) Cold working as much as 10 per cent prior to aging or re-solution treating plus aging has little influence on the modulus measured after aging. Cold working 60 per cent followed by aging results in a modulus of approximately 31 x 10^6 psi perpendicular to the rolling direction, 26 x 10^6 psi at 45 degrees, and 27 x 10^6 psi parallel to the rolling direction. Re-solution treating after 60 per cent cold work followed by aging essentially removes the effect of cold working on modulus.

(4) The variations in modulus observed are not significant in influencing most critical design applications. Incorporation into design of the anisotropic behavior of Young's modulus may be desired if strain compatibility is a predominating requirement or if the most efficient elastic behavior is desired in the presence of steep stress gradients.

Fracture Toughness in Plate Thicknesses of 18 Per Cent Nickel Maraging Steels

by Richard E. Lewis, Lockheed Missiles and Space Company

In a program to evaluate the fracture toughness of certain high-strength steels in plate thicknesses of 1 inch and less, both the 200 and 250 grades of 18 per cent nickel maraging steel were included. The effect of composition and processing history on resistance to crack propagation was of particular interest. Resistance to crack initiation was not included in the program.

The steels were obtained in plate thicknesses of 3/16, 3/8, and 1 inch. The composition of the 18Ni(200) grade was to be controlled so that the resultant plate would hopefully attain 200,000 ± 10,000-psi yield strength after solution annealing at 1500 F for 1 hour per inch of thickness and aging at 900 F for 3 hours. The 18Ni(250) grade plate was to reach 250,000 ± 10,000 psi in the same manner. However, with a few exceptions, principally the thickest plate, the yield strengths did not fall into the desired ranges. Perhaps factors of composition and processing contributed to the divergence.

Specimens for fracture-toughness evaluation were extracted from the plate, finish machined, and aged. The specimens were Charpy V-notch specimens which had been precracked by fatiguing. Their dimensions were identical with the ASTM or Federal Standard, except for width, which was varied from 0.063 to 1.000 inch.

The study included testing of specimen widths up to 1 inch from plate materials up to 1 inch thick. Four principal orientations of specimen and notch were used: transverse with through-the-thickness notch, longitudinal with through-the-thickness notch, transverse with surface notch, and longitudinal with surface notch. With the exception of one series to investigate variation in fracture toughness of 1-inch-thick plate of the 200 grade, the specimens were always extracted so that one lateral surface was identical with the original rolled plate surface. Specimens were all tested at room temperature and at a relative humidity of 50 to 60 per cent.

The W/A values reported were the observed energy to propagate the crack through the precracked specimen upon impact, divided by the projected area of the fracture surface produced. The fatigue-precracked area was not counted, of course.

The fatigue precrack produced at the root of the machined notch was nominally 0.020 to 0.030 inch deep and was perpendicular to the longitudinal axis of the specimen. Some specimens tested had fatigue-crack depths outside of this range.

The variation of fracture toughness through the thickness of 1-inch plate of the 18Ni(200) grade was studied with both longitudinal and transverse specimens having through-the-thickness notches. The results showed that the longitudinal specimens yielded consistently higher results than did the transverse, regardless of location. In addition, the center location appeared to exhibit somewhat higher resistance to fracture than did the material near the surfaces for the same crack-propagation direction.

The influence of specimen width was studied for 1-inch-thick plate, and the results were compared with the generally predicted curve of specimen thickness vs. center-notched or edge-notched tensile fracture toughness. Specimen widths of nominally 3/16, 3/8, 1/2, 3/4, and 1 inch were used, and both the 18Ni(200) and the 18Ni(250) grades were included in the study. The types of specimens used were longitudinal with through-the-thickness notch and longitudinal with surface notch.

For either grade, the results indicated that the W/A values obtained were not influenced by the orientation of the notch. The data did appear to follow the same type curve as predicted for variation in specimen width. The fracture toughness of the 200 grade was consistently higher than that of the 250 grade, regardless of specimen width or orientation. The shelf reached in specimens 1/2 inch wide and wider encourages consideration that an "apparent" plane-strain fracture toughness may be indicated. For the 200 grade the data produced a scatter band from 1000 to 1300 in-lb/in.^{2}, with a mean value of 1150 in-lb/in.^{2}. Assuming a modulus of elasticity of 27 x 10^6 psi and a Poisson's ratio of 0.30, the calculated K_{Ic} for these values of strain energy density were 172,500 to 196,800 psi $\sqrt{in.}$, with a mean value of 185,000 psi $\sqrt{in.}$

Similarly, for the 250 grade, apparent K_{Ic} values of 129,800 to 150,000 psi in. with a mean value of 139,000 psi $\sqrt{in.}$ were obtained. However, for both grades, there was some measurable amount of shear in the fracture surface, which led the author to suspect that these calculated values of plane strain were somewhat high.

A series of tests was also performed to investigate the possible effect on fracture toughness of hot rolling material of the same composition to various thicknesses. In other words, this study was aimed at the effect of plate thickness on the amount of fracture toughness shown. Specimens with widths ranging from 1/16 to 1 inch were used.

For both the 200 and 250 grades, the observed fracture toughness seemed related to specimen width rather than to plate thickness. The pattern of the width effect followed the generally predicted curve. However, there was some indication that an increase in fracture toughness above that attributable to specimen width occurred in the 200 grade, 3/8-inch-thick plate, as compared with the 1-inch thick plate. A specimen about 1/8 inch wide of the 200 grade, 3/16-inch-thick plate appeared to have the highest fracture toughness. Specimen widths larger or smaller than 1/8 inch resulted in lower values.

For the 250-grade series, the 3/8-inch-thick plate again exhibited somewhat higher values than expected from the 1-inch-thick plate. Data for the 3/16-inch-thick plate appeared to more closely fit an extrapolation from 1-inch plate than from 3/8-inch plate.

The author concluded that there are no severe discrepancies in fracture-toughness characteristics produced by hot rolling to 3/16-, 3/8-, or 1-inch thicknesses, although minor trends may be noted. The 200 grade consistently showed approximately two times the resistance to crack propagation of the 250 grade for any particular specimen width.

As some difficulty was encountered in maintaining fatigue-crack depth to the 0.020 to 0.030-inch originally desired, data were obtained on the influence of this variable on observed fracture toughness as shown by precracked Charpy-impact specimen. Specimens 3/16, 3/8, 1/2, and 3/4 inch wide from the 200 grade, 1-inch-thick plate were tested. A plot of fatigue-crack depth versus impact-energy density provided evidence that a relationship did exist. No exr anation has been found for this phenomenon.

<u>Some Microstructural Aspects of Maraging (250) Steel in Relation to Strength and Toughness</u>
by G. E. Pellissier, United States Steel Corporation

The author observed that the maraging steels have excited more than routine curiosity because of the unusually large increments in strength that are obtained by suitable aging treatments, and because their fracture toughness is greater than would be predicted from curves relating strength with fracture toughness that are empirically established for the quenched-and-tempered low-alloy steels. With reference to the first feature, the author commented that considerable effort and skill have been required to identify the principal

microstructural source of the strengthening that occurs during aging in these alloys. At present, our comprehension of the fine-scale microstructures, and of the strengthening mechanisms, is not adequate to satisfactorily explain the strength-toughness relationships observed. The second feature of the steels is illustrated by comparative measurements of plane-strain fracture toughness, at a yield-strength level of about 240,000 psi, which consistently have shown that the 18Ni(250) maraging steel is considerably tougher at room temperature (G_{Ic} = 200 ipsi) than quenched-and-tempered 0.3 to 0.5 per cent carbon, low-alloy steels (G_{Ic} = 30 to 50 ipsi), even though the Charpy V-notch impact test shown by energy levels (about 15 foot-pounds) are not significantly different for the two classes of steel.

This report is a brief summary of preliminary observations made in the Applied Research Laboratory on the microstructures in maraging (250) steel, as they relate to strength and toughness.

An electron-microscope study of extraction replicas from deeply etched specimens supplied the finding that a fine dispersion of precipitate particles is present in the steel as austenitized and air cooled. By means of electron diffraction, these particles were identified as titanium carbide, titanium nitride, or titanium carbonitride; since the diffraction patterns of these compounds are virtually identical, unique identification is not possible.

High-resolution transmission electron microscopy of ultrathin foils of the austenitized and air cooled material revealed several interesting features of the fine-scale microstructure. The martensite grains are roughly equiaxed or plate-shaped in contrast to the acicular, pencil-shaped martensite grains found in the 0.3 to 0.5 per cent carbon low-alloy steels. Many of the boundaries are so sharply delineated as to suggest some unusual chemical or structural heterogeneity; this possibility is being explored further. A very high density of dislocations is observed in the martensite grains, but relatively few twins can be found, in contrast to the carbon martensites.

The microstructure of normally aged 18Ni(250) maraging steel was found by means of extraction-replication electron microscopy and transmission electron microscopy to contain an extremely fine and dense precipitate which undoubtedly is the main source of the strengthening by aging. Electron-diffraction patterns obtained both from the extracted particles and from particles in situ in the ultrathin steel foils closely matched the published pattern for Ni_3Mo. However, the author believes that, because the steel contains titanium and because titanium contributes an additional strengthening increment upon aging, over and above that provided by the molybdenum, precipitates of both Ni_3Mo and Ni_3Ti are present in the aged structure. Unfortunately, direct unequivocal evidence of Ni_3Ti cannot be obtained from the electron diffraction pattern because of line coincidence.

Electron-microprobe analyses were made from several extraction replicas of aged steel. The extracted precipitate was found to contain about 30 Mo, 30 Ni, 20 Fe, 10 Ti, and 10 Co, in weight per cent. This analysis indicates an excess of molybdenum over that required to form Ni_3Mo from all of the available nickel. Although the iron and cobalt possibly may substitute in the Ni_3Mo structure to give the stoichiometry $(Ni,Co,Fe)_3Mo$, which would agree roughly with the relative amounts of four of the elements determined,

the formation of titanium compounds (such as Ni_3Ti) is excluded, unless they be carbides and nitrides.

A high-resolution electron-transmission micrograph of an ultrathin foil specimen was prepared from the normally aged steel. Two types of extremely small precipitate particles were present; the majority were in the form of ribbons on dislocation lines and at martensite subboundaries, and the minority were smaller, disk-shaped or spherical particles rather randomly distributed throughout the matrix. It is believed that the ribbons were Ni_3Mo, and that the disks were Ni_3Ti. As an indirect effort to establish the identity of the disks, a steel of very similar composition, which contained 0.2 per cent aluminum in place of any titanium, was examined after aging in the same manner. A profusion of Ni_3Mo ribbons was quite evident, but there was no trace of the disks that were observed in the titanium-bearing steel. This finding would seem to indicate that the disks did involve titanium.

For relatively low heating rates, such as obtained in aging treatments, and for aging times or temperatures greater than those normally used, the nickel-rich precipitates (Ni_3Mo and Ni_3Ti) evidently redissolve in the matrix to form, by a diffusion reaction, platelets of austenite that is sufficiently enriched in nickel to be stabilized to the degree that it does not revert to martensite on cooling to room temperature. Electron-probe microanalyses of the austenite extracted in replicas from overaged specimens showed that the nickel content of the austenite increases with the degree of overaging. By means of X-ray diffraction analyses, the amounts of reverted austenite, formed upon overaging at 900, 950, and 1000 F for various times, were determined. The results indicated that, for each aging temperature, there is a characteristic time beyond which reversion to austenite proceeds quite rapidly.

Many fractured tension-test specimens of these steels, which were oriented in the longitudinal direction of the rolled plate, exhibited longitudinal "splits" oriented parallel to the rolling plane and direction. Similarly, fractures of notched-round, fatigue-cracked, tension-test specimens (longitudinal) that were used for plane-strain fracture toughness measurements (G_{Ic}) showed "internal shear lips" oriented parallel to the rolling plane and direction. Light-microscope examination of polished, but unetched, longitudinal sections through these specimens near the fracture surface did not reveal any unusually high concentrations of nonmetallic inclusions associated with the deep cracks intruding from the main fracture surface, as initially was suspected. However, investigation of the same sections after etching revealed light and dark bands, together with bands of an unetched phase, through which the intruding cracks (splits) had propagated. The white was identified as austenite, and it was established that this austenite was present in the steel before aging, so that it was residual austenite, in contradistinction to the reverted austenite formed by overaging.

These findings strongly suggested that chemical heterogeneity, probably arising from interdendritic microsegregation during solidification of the ingot, was responsible for the observed banding and for stabilization of the residual austenite associated with the bands. Therefore, further investigation of this suspected chemical heterogeneity was carried out with the electron-probe microanalyzer on polished and etched longitudinal sections of rolled plate. The results indicated that the observed banding and residual

austenite are caused by persistent chemical microsegregation of nickel, molybdenum, and titanium.

Subsequent to these observations, an experiment was conducted to determine whether a prolonged, high-temperature annealing treatment would obliterate the segregation by thermal diffusion of the segregated elements. Pieces of plate materials were annealed at 2300 F for 16 hours, air cooled, and then were normally austenitized and aged. The segregation was essentially eliminated, but tensile tests of longitudinal notched specimens indicated that the homogenized material was not as tough as the initial heterogeneous material.

Light-microscope examination of polished-and-etched sections cut normal to the plane of fracture showed that the fractures were predominantly intergranular, along prior austenite grain boundaries. Electron micrographs of plastic replicas of such sections revealed that very localized and severe plastic deformation had occurred during the essentially plane-strain fracture process along the prior austenite grain boundaries; the depth of obvious metal flow was only about 1 micron. Further electron-microscope investigation of the finer-scale microstructure of this homogenized steel, utilizing both extraction-replica and thin-foil transmission techniques, revealed a pattern of interconnecting "canals", corresponding to prior austenite grain boundaries, within which there was no visible strengthening precipitate. To a much lesser degree, similar precipitate-denuded regions were observed at martensite grain boundaries. It was the author's opinion that this more-or-less continuous, thin film of weaker metal in the grain-boundary regions affords a preferred path for fracture propagation and results in relatively low-energy fractures, which are ductile on a microscopic scale, even under essentially plane-strain conditions. In addition to the denuded regions, "stringers" of a segregate phase, which might consist of coalesced sheets of one of the strengthening precipitate compounds, frequently were noted in the boundary proper.

These findings led to a more exhaustive re-examination of the fine-scale microstructure of the steels which had been subjected only to the normal heat treatment, with the result that evidence for precipitate-denuded regions in the vicinity of martensite grain boundaries and subboundaries also was found in these materials, although to a lesser degree than in material homogenized first at 2300 F. Furthermore, investigation of the contour of plane-strain fractures in these normally treated steels, by means of electron microfractography, has suggested that the fracture may be largely intergranular.

Fracture-toughness measurements were made on a 1-inch plate of the 18Ni(250) steel using precracked Charpy V-notch type specimens oriented in the plate in various directions. The G_{Ic} value obtained from the longitudinal specimen with a through-thickness notch was 195; for the transverse specimen with a through-thickness notch it was 185; for the longitudinal specimen with a surface notch it was 245; while the short transverse specimen with the notch parallel to the rolling direction gave a value of 100. The low crack toughness measured in the last orientation provides strong support to the concept of the influence of banding and residual austenite on anisotropy of toughness in these steels.

To obtain some direct, visual evidence of the effect of the banding on the microscopic path of fracture in these variously oriented broken test specimens, light-microscope examinations were conducted on polished-and-etched

sections cut normal to the plane of fracture. The fracture profile representing the first two specimen orientations did not exhibit any pronounced influence of the banding on the microscopic path of the fracture, but the profile of the third specimen did show quite clearly that the fracture frequently "detoured" abruptly from its main course upon encountering segregation bands at approximately normal incidence. A comparatively rough, jagged fracture surface was created thereby. It was rather difficult to determine whether these crack excursions or intrusions occurred within the bands or along the band-matrix interfaces. In the case of the last type of orientation, the fracture occurred predominantly through bands, occasionally "stepping" up or down from one band to another through interconnecting bands, as was anticipated.

Notes on Electron Microscopy and Phase Identification Relative to the 18Ni(300) Maraging Steel

by B. R. Banerjee, Crucible Steel Company of America

A preliminary report was given of an investigation into the microstructural features and physical metallurgy of the 18 per cent nickel maraging steels. The steel under study was of the nominal 300,000 psi grade with a 0.2 per cent offset yield strength of 271,000 psi, a tensile strength of 280,000 psi, and a K_c calculated to be 212, after the standard heat treatment. The material had been consumable-electrode vacuum-arc remelted.

Several electron micrographs of extraction replicas and surface replicas were shown and discussed. As expected, the appearance of the micrographs changed with the aging conditions. However, they also changed with the etchant used to prepare the metal specimen. Thus, the features shown in a replica representing metal etched with a picral-HCl reagent differed from those seen when the etchant was dilute HNO_3. These observations serve to emphasize the importance of methodology in research.

A number of analyses of extracted precipitates were also presented. In one case the reagent was ammonium chloride plus citric acid, in another it was phosphoric acid in water, and in a third it was 10 per cent aqueous nitric acid. In all cases, the results differed especially with respect to the nickel, molybdenum, and titanium contents. One of the conclusions drawn from this study was that caution must be exercised in interpreting analytical results obtained on extracted precipitates; the composition may be strongly influenced by the extraction method.

Of great interest were data indicating that the chemical composition of the precipitate, or precipitates, changed with the aging temperature. This certainly suggests that a number of factors in the nature of the precipitates are sensitive to aging conditions. It was estimated that both Ni_3Mo and Ni_3Ti were present in various amounts.

<u>Evaluation of Maraging Steel at U. S. Army Materials Research Agency</u>
by Eric B. Kula and Charles F. Hickey, Jr.,
U. S. Army Materials Research Agency

Measurements of tensile and impact properties have been made at temperatures down to 4 and 10 K, respectively, on two heats of 18 per cent nickel maraging steel in the form of 1/2-inch-thick plate. Prior heat treatment consisted of solution annealing at 1500 F for 1 hour and air cooling, followed by aging at 900 F for 3 hours. The results of the tests showed that the yield and tensile strengths increased continuously as the test temperature decreased. The elongation decreased only slightly with decreasing temperature, whereas the reduction of area showed a sharp decrease for one heat below -196 C. The Charpy-impact energy also decreased with decreasing test temperature. For one heat, it dropped from 20 to 3 ft-lb between room temperature and -263 C. The other heat which showed somewhat greater ductility at the lowest temperature also had greater impact energy at this temperature.

The authors compared these properties with those of other materials. They reported that annealed stainless steels can exhibit impact energies of 80 ft-lb at -263 C, and reductions of area greater than 50 per cent. Titanium and aluminum alloys suitable for low temperature use also show better properties than the maraging steels at -263 C. For example, the titanium alloy 6Al-4V shows 32 per cent reduction of area and 14 ft-lb at this temperature. Compared with high-strength, low-alloy steels, the maraging steels fare better; although data are limited. Many alloy steels have elongations or reductions of area of almost zero, and impact energies of only 1 or 2 ft-lb at -263 C. Another measure of the temperature sensitivity is the increase in yield and tensile strength with decreasing temperature. The increase in yield strength between room temperature and -269 C is from 242,000 to 344,000 psi, 102,000 psi, compared with 133,000 to 240,000 psi, 107,000 psi, for 6Al-4V. This is less proportionately than for alloy steels which are embrittled at low temperatures.

True stress-strain curves were presented. Of special interest was the curve for -269 C, which showed a large serration. Serrated stress-strain curves are typical at this temperature, although the number and size of the serrations vary from material to material. In the steel tested at AMRA most of the deformation was limited to the region of the neck and took place during one or two load drops. It was noted also that the strain at maximum load, often termed the strain-hardening exponent, was quite low.

The variation of tensile elongation in sheet specimens as a function of thickness can be studied by measuring the elongation in a number of different specimens. In practice, it is simpler to measure the elongation over different gage lengths on a single specimen. It is generally accepted that if the "slenderness ratio", $L/\sqrt{A}$, (L = gage length, A = specimen area) is maintained constant, the elongation is then constant. For example, the elongation in 2 inches on a specimen of area, A, can be determined by measuring the elongation in a bar of Area, A_2, over a gage length L, where $L = 2\sqrt{A_2/A_1}$. This procedure is valid provided a plot of elongation versus $L/\sqrt{A}$ is linear.

The elongation was plotted as a function of $L/\sqrt{A}$ for a 1/2-inch-square bar and a 1/2 by 0.130-inch bar given the aforementioned standard heat treatment. The curves were linear over a considerable range and had about the same slope, i.e., 0.89. The authors noted that this slope is very high and indicates a strong variation of elongation with sheet thickness.

The effects of several thermomechanical treatments were explored. For example, when the steel is deformed in the annealed condition and then maraged, the strength and hardness increase. A reduction of 60 per cent by rolling led to an increase in yield strength from 232,000 to 255,000 psi, an increase of approximately 10 per cent. The ultimate tensile strength and hardness increased in a similar fashion. Again, for the steel cold worked during cooling from the solution-treatment temperature, but above the M_s temperature, at 650 F, and then maraged, the yield strength increased from 247,000 to 265,000 psi, an increase of approximately 7 per cent. Accompanying this was a very small change in hardness. When the steel was worked in the maraged condition, the yield strength showed little change or actually decreased, while the tensile strength showed an increase of only 10,000 psi. The hardness also decreased slightly. Finally, when the steel was given a reage after having been worked in the maraged condition, a further increase in strength was obtained. The yield strength increased from 249,000 to 268,000 psi with a 60 per cent reduction, accompanied by an increase in tensile strength and hardness.

Fracture toughness was also measured on specimens which were cold rolled prior to maraging. Specimens used were the 3-inch-wide center-notch Irwin-type specimen. The specimens were fatigue cracked prior to testing, and the critical crack size was determined by an electric-potential technique. Tests were carried out on longitudinal specimens and on specimens cut transversely and rolled in this direction (i.e., cross rolled). In addition to testing in the final thickness, which varied with the amount of reduction, specimens were machined to a final thickness of 0.038 inch and tested. Scatter in the data obtained was apparent. Values of K_c ranged from 161,000 to 309,000 psi $\sqrt{\text{in.}}$ for the longitudinal specimens reduce 40 per cent. It was concluded that the fracture toughness decreases with increasing strength level (cold work) when measured on sheet of varying thickness. This variation was reduced somewhat when sheets of constant thickness were measured.

Measurements were made of Young's modulus, Poisson's ratio, and the anisotropy parameter, R, which is equal to the ratio of the width-to-thickness strain in the plastic region. The tests were made on material cold worked 0, 20, 40, and 60 per cent after annealing but before maraging. Young's modulus was found to be 26 x 10^6 psi for each condition. Poisson's ratio varied from 0.26 to 0.38, while R ranged from 0.60 to 0.91.

Finally, the effect of test temperature over the range of +68 to -71 C was studied. Specimens were tested in the transverse direction both in the standard heat-treated condition (1500 F for 1 hour and 900 F for 3 hours) and after having been cold rolled 50 per cent prior to maraging. The thickness was 0.10 inch in each case. Tests were carried out with standard tensile specimens, the Brown edge-notch specimen (1 inch wide, 0.001-inch notch radius maximum), and the Irwin type (3 inches wide, center notch, fatigue cracked). The results obtained showed that for the standard treatment there was no great effect of test temperature over this range on the notched properties, although

the yield and tensile strengths did increase with decreasing test temperature. The toughness in the longitudinal direction was higher than that in the transverse direction. Cold working prior to maraging was found to increase the strength at all test temperatures. The notch strength determined on the edge-notch specimen was lower than for the standard treatment and showed little variation over the temperature range investigated. In contrast to this, the fracture toughness (K_{c3}) showed a decrease below room temperature, so that the toughness was greater at high temperature and lower at the low testing temperatures than for the lower strength standard condition.

Effects of Unidirectional Solidification on the Properties of 25 Per Cent Nickel Maraging Steel
by D. F. Armiento, Frankford Arsenal

The mechanical properties of unidirectionally solidified castings have been reported to be superior to those of standard sand castings with respect to improved ductility at comparable strength level. For example, the author reported that in a unidirectionally solidified casting of 4340 steel the mechanical properties parallel to the columnar grains averaged 209,000-psi yield strength, 260,000-psi tensile strength, and 31 per cent reduction of area; in the transverse direction the properties averaged the same in yield strength and in tensile strength with 9 per cent elongation. In a comparable sand casting, the average properties were respectively 225,000, 275,000, and 6 per cent.

The improvement in properties obtained by unidirectional solidification is attributed to (1) reduction of microporosity, (2) improved chemical homogeneity on a micro and macro scale, and (3) decreased inclusion count. It is considered possible that the improvement can be achieved in wrought products as well as castings by using ingots which have been unidirectionally solidified. This possibility was investigated with a maraging steel.

At the time this investigation was initiated, the 20 and 25 per cent nickel maraging steels were being developed. Since the 25 per cent nickel maraging steel showed promise of developing higher strength levels it was selected for study. This material is austenitic after solution treating at 1500 F and can be hardened by either of two treatments. The first treatment consists of cold rolling approximately 65 per cent followed by subzero treating to transform the austenite to martensite, and maraging at 850 F. The second treatment involves an ausage at 1300 F for 4 hours followed by a subzero treatment to transform the austenite to martensite, and maraging at 850 F.

For commercially produced material, the International Nickel Company reported the following nominal results: The first treatment resulted in a yield strength of 243,000 psi with a K_c (fracture toughness) of 204,000 psi $\sqrt{in.}$ and the second treatment resulted in a yield strength of 248,000 psi with a K_c of 111,000 psi $\sqrt{in.}$ It will be observed that the ausaging treatment resulted in a lower value of fracture toughness, probably due to a precipitation of titanium compounds in the prior austenite grain boundaries.

Since the objective of this work was to increase the useful strength of the alloy through improved ingot-casting techniques with an improvement in fracture toughness, the total hardener content of the material was increased.

Thus, 1.70 to 1.90 per cent titanium and 0.30 to 0.50 per cent aluminum were specified, instead of the 1.3 to 1.6 and 0.15 to 0.35 per cent ranges usually used.

Six heats of the alloy were vacuum induction melted. Of the six ingots cast, four were unidirectionally solidified and two were allowed to solidify in the conventional manner. The ingots were cylindrical in shape and were approximately 4 inches in diameter and 4 inches high. The ingots were press forged to 1-3/8 by 6 by approximately 6 inches without reheating. Finishing temperature was approximately 1600 F. The forged slabs were air cooled after forging. After cooling, 1/16 inch was machined from each surface, thereby reducing the thickness to 1.250 inches. The slabs were then hot rolled to approximately 1/8-inch thickness, blast cleaned with steel shot, and side trimmed to 6 inches wide. The sheets were cold rolled without annealing to 0.045 to 0.052 inch thick in five passes.

Standard strip tensile test specimens according to Specification QQ-M-151a were cut in both the longitudinal and the transverse direction of the sheet. Since this material was cold worked 60 to 65 per cent, the first method of hardening was tried. The specimens were cooled at -100 F for 16 hours and maraged at 850 F for 3 hours. This treatment resulted in 223,500-psi yield strength, 285,600-psi tensile strength, and 2.5 per cent elongation. These values are somewhat lower than would be anticipated from the total hardener content of the alloy.

Consequently, the second hardening procedure, namely, solution anneal at 1500 F for 1 hour, ausage at 1300 F for 4 hours, cool at -100 F for 16 hours, and marage at 850 F for 3 hours, was tried. This treatment gave 279,000-psi yield strength, 293,100-psi tensile strength, and 3.5 per cent elongation. These properties are consistent with those anticipated from the total hardener content of the alloy. All the specimens were treated using this procedure.

The unidirectionally solidified material showed higher tensile properties than did the comparable conventionally solidified material. The specimens transverse to the rolling direction showed higher mechanical strengths than did the specimens cut longitudinal to the rolling direction. However, the transverse elongation was less than the elongation in the longitudinal direction.

Center-notched fracture-toughness specimens, 4 by 12 inches, were machined from each sheet in the longitudinal direction. After hardening, a 1-inch-long central slot was cut in the specimen by electrodischarge machining. Prior to testing, the specimens were precracked in fatigue by bending. The fracture toughness was determined using the crack-opening displacement technique.

The values of fracture toughness obtained in terms of K_c showed that unidirectional solidification had a very small if any effect on the fracture toughness of this material. These data are in accord with unpublished data obtained by Frankford Arsenal on tempered martensitic low-alloy steel unidirectionally solidified.

The fracture toughness of these various heats of 25 per cent nickel maraging steel was approximately only 20 per cent of the values anticipated. An investigation was made of the structure of the fracture toughness specimens. These structures showed extreme banding characteristic of segregation, although the unidirectional solidification process was intended to minimize this effect. The white bands observed were thought to be retained austenite.

High titanium contents tend to promote retention of austenite and segregation. The titanium content of all these heats was considerably higher than the usual maximum. The stability of the retained austenite was reflected in the lower mechanical properties obtained on the cold-rolled, subzero-treated and maraged samples of this steel. The solution anneal, ausage plus subzero cool, and marage treatment resulted in a reduction in the total retained austenite content which was reflected in the higher mechanical properties obtained. It was felt that the weakening effect of retained austenite laminates plus the embrittling effect of precipitation during ausaging resulted in the very low values of fracture toughness observed.

In view of the preceeding discussion, the following heat treatment was developed to minimize the retained austenite: (1) solution anneal at 1550 F for 1 hour, air cool to room temperature, and cool in liquid nitrogen, (2) ausage at 1300 F for 4 hours, air cool to room temperature, and cool in liquid nitrogen, and (3) marage at 850 F for 3 hours. This treatment was not successful in eliminating the retained austenite completely but did reduce it considerably. The fracture toughness of the samples which were reheat treated according to the new heat treatment was approximately 50 per cent greater than those of samples given the standard treatment. These data support the contention that the retained austenite was partially responsible for the low values of fracture toughness.

SESSION IV - GENERAL MARAGING STEEL EVALUATIONS

Evaluation of 18 NiCoMo (300), 9Ni-4Co, H-11 and SAE 4340 Steel Forgings
by Richard L. Jones, General Dynamics - Fort Worth

This paper briefly presents the results of a year's testing on high-strength steel forgings which were being considered for possible application as landing gear material. Primarily, the investigation was concerned with 18Ni(300) maraging steel and 9Ni-4Co Republic steel, although SAE 4340 and H-11 steels were also examined to provide comparative data. The materials were evaluated with respect to tensile properties, fatigue properties, and resistance to stress-corrosion cracking.

One axle forging and three shock-strut forgings were closed-die forged from each of the principal materials. One 18Ni(300) maraging-steel forging was overheated 350 F during forging, while one 9Ni-4Co steel forging was overheated 150 F. The SAE 4340 was evaluated as an axle forging and a 4 by 12 inch billet. All of the H-11 steel specimens came from a 4 by 12-inch billet.

The heat-treating practices adopted were designed to develop the optimum tensile properties in the high-strength range of 260,000 to 290,000 psi. The 18Ni(300) steel was solution treated 4 hours at 1500 F and aged 3 hours at 900 F. The 9Ni-4Co steel was normalized 1 hour at 1600 F, austenitized 1 hour at 1450 F and quenched in warm agitated oil, then tempered 1 hour at 400 F, quenched to -112 F for 2 hours, and tempered 2 hours at 450 F. The SAE 4340 steel was normalized 30 minutes at 1650 F, austenitized 30 minutes at 1550 F and quenched in warm agitated oil, and tempered 2 hours at 475 F. The H-11 was austenitized 30 minutes at 1850 F, double tempered 2 hours each at 1025 F, and final tempered 2 hours at 1050 F.

From the tensile-test results, it was apparent that the 18Ni(300) steel had superior strength to the other three materials, particularly with respect to yield strength. The yield strength exceeded by approximately 55,000 psi the yield strength of the other steels. This steel had a very high yield/ultimate ratio of 0.97. The yield and ultimate strengths of the 9Ni-4Co, 4340, and H-11 were comparable. The ultimate strength of the 18Ni (300) steel was approximately 20,000 psi higher than the ultimate strength of the other steels.

The notch-ultimate strength of 18Ni(300) steel was superior to that of the other materials investigated. However, its short transverse properties were considerably less than its longitudinal properties. The 9Ni-4Co was superior to 4340 and H-11 in notch strength. In the longitudinal direction both the 18Ni(300) and the 9Ni-4Co steels had notch-ultimate ratios of 1.0 or greater.

From the standpoint of ductility, the maraging steel and 4340 were comparable in both grain directions. In the short transverse direction, the ductility of the 18Ni(300) steel and the 4340 suffered a greater decrease than did that of the 9Ni-4Co steel. These three materials had comparable reduction in area in the longitudinal direction. H-11 steel had good reduction of area in the transverse direction.

In tension-tension axial fatigue, the 9Ni-4Co steel was somewhat superior to the 18Ni(300) maraging steel. For example, for smooth bars in the longitudinal direction, the limit at 10^7 cycles for the 9Ni-4Co alloy was 134,000 psi while for the maraging steel it was 114,000 psi. In the short-transverse direction, the values were 129,000 psi and 98,000 psi for smooth specimens, respectively, and 77,000 psi and 59,000 psi for specimens with a notch having a K_t of 2. The overheated 18Ni(300) steel had lower fatigue strength than did the properly forged material.

Low-cycle axial-fatigue tests were run at a frequency of 0.02 cps and with R = O. There was practically no difference in the low-cycle fatigue life of longitudinal and short-transverse specimens of the 9Ni-4Co steel. The low-cycle fatigue strength of 9Ni-4Co was superior to that of the 18Ni (300) alloy. In the short transverse direction, the life of the 18Ni(300) steel was significantly less than in the longitudinal direction. The overheated 9Ni-4Co forging showed definitely reduced fatigue strength. The overheated 18Ni(300) forging had as good fatigue properties as the properly forged material.

The stress-corrosion properties of the four steels evaluated in this program were investigated under two conditions. The first condition involved alternate immersion in 5 per cent NaCl of round, unnotched test specimens which were subjected to constant load. This load was generally 200,000 psi although it was lowered to approximately 75 per cent of the ultimate strength for those test specimens heat treated to less than 260,000 psi ultimate strength. The alternate-immersion cycle consisted of 5 minutes in the salt solution followed by 15 minutes in air. This cycle was repeated until failure occurred or until the time period reached 200 hours.

The other stress-corrosion test condition involved this same alternate-immersion cycle in 5 per cent NaCl; however, the test coupon was a flat specimen 1 inch wide by 0.060 inch thick. It contained a fatigue crack partially progressed into one surface. This center fatigue crack was produced by cantilever bending the specimen over a sharp point. The partial-cracked specimen was subjected to a constant 150,000-psi stress until failure occurred.

Nearly all the unnotched test specimens were short-transverse specimens, whereas the cracked specimens were transverse.

The results obtained indicated that the 9Ni-4Co steel had stress-corrosion properties vastly superior to those of the other three materials when investigated in the form of smooth specimens. The short-transverse specimens of the 4340 steel had very poor stress-corrosion resistance. The H-11 steel appeared to have slightly better properties than the 18Ni(300) steel, but this comparison was not well established because the H-11 was in billet form rather than forged shape. The two martensitic steels investigated, H-11 and 4340, had stress-corrosion properties which were improved by lowering the ultimate strength.

When the cracked stress-corrosion specimens were used, the 9Ni-4Co steel lost most of the stress-corrosion resistance it exhibited in the unnotched condition. It had next to the poorest properties of the materials investigated. On the average, the 18Ni(300) steel was the best of the materials. The SAE 4340 steel had very low stress-corrosion properties. The longest stress-corrosion life was achieved by one of the specimens of H-11 steel. However, another H-11 sample failed on loading while two more failed while cracking.

Using center-notched fatigue-cracked sheet tensile specimens, 0.180 by 3 by 12 inches, data were obtained indicating that vacuum-melted 4340 had the highest notch strength at room temperature among the materials studied. The 18Ni(300) steel was next, followed by 9Ni-4Co. At -65 F, however, the 9Ni-4Co had lost little of its room-temperature notch strength, whereas the 18Ni(300) steel and the 4340 suffered considerably.

<u>Investment Cast Maraging Steel by the Monoshell Process</u>
by R. J. Wilcox, Misco Precision Casting Company

Maraging steel castings were successfully produced by the double vacuum Monoshell Process. Quality level as determined by visual, X-ray,

magnetic-particle, and fluorescent-penetrant examination compared favorably with high-quality investment castings made from other alloys. While maraging steel develops strength levels among the highest studied to date for investment castings, it is indicated that the ability to develop full strength and ductility capabilities from test bars cut from castings depends upon the degree of soundness and freedom from microporosity that can be achieved by means of sound design and gating practice. It is indicated in sections greater than 1 inch that there may be some difficulty in developing ductility levels comparable with those resulting from separately cast test bars of smaller cross section. In castings with section size approximately that of test-bar sections, satisfactory strength and ductility levels would be expected, depending on the effectiveness of gating practice to produce castings with minimum microshrink.

Heat-treatment studies showed that the optimum practice for the 18 per cent nickel grade should consist of air cooling from 2100 F for annealing or homogenization, followed by maraging at 900 F.

Test bars cast to the wrought-alloy composition showed somewhat higher strength than did those made from the recommended casting composition. The former showed ultimate and yield strength up to 270,000 psi and 254,000 psi, respectively, compared with 253,000 psi and 242,000 psi respectively for the latter.

Studies at elevated temperatures indicated that useful strength levels are maintained up to approximately 800 F, after which the drop in ultimate and yield strengths begins to accelerate.

Fracture Toughness and Stress Corrosion
Testing of High Strength Steels
by Robert A. Davis, The Boeing Company - Airplane Division

An investigation is being undertaken to correlate stress-corrosion cracking data with fracture-toughness values. The alloys under study are 4340, 4335M, H-11, D6ac, 18Ni(300), 18Ni(250), 9Ni-4Co, and 17-4PH. Information on both longitudinal and transverse specimens is being obtained.

Plate material approximately 3/8 by 10 by 48 inches is being used in the program. Stress-corrosion and fracture-toughness-specimen blanks were removed from the transverse and longitudinal directions. The specimens were heat treated to develop ultimate strengths in the 200,000 to 300,000-psi range. Fracture-toughness specimens were cyclically loaded to produce a fatigue crack approximately 0.5 inch long and were then loaded to failure. Stress-corrosion specimens were loaded to 80 per cent of the 0.2 per cent yield strength and alternately immersed in a 3.5 per cent salt (NaCl) solution. The cycle consists of approximately 8 minutes in solution and 52 minutes out of solution.

For most of the steels, the mechanical properties were almost identical in the transverse and longitudinal directions of the plate. The 9Ni-4Co steel showed some variation between longitudinal and transverse strengths. The fracture-toughness properties were more sensitive to orientation, but they did not appear to behave in a consistent pattern. For the

18Ni(250) and the 0.43 per cent carbon 9Ni-4Co steels, the transverse fracture-toughness values were higher than the longitudinal values. For the 0.30 per cent carbon 9Ni-4Co steel and the low-alloy steels, the longitudinal properties were superior. The 17-4PH steel had one transverse fracture-toughness value higher and one lower than the longitudinal values. The author considered that this inconsistency in behavior points up the importance that mill processing may have in influencing final mechanical and fracture-toughness properties.

The data showed that there was a correlation between fracture toughness and stress-corrosion susceptibility for all the steels except the precipitation-hardening stainless steel, 17-4PH. In general, the higher the fracture toughness, the better the resistance to stress corrosion. The maraging-steel data indicated a very wide variation between the 300,000 and 250,000-psi compositions. The 18Ni(300) steel showed a very low fracture toughness and a very high susceptibility to stress-corrosion cracking. Although the stress-corrosion evaluation was not complete on the 18Ni(250) steel, the high fracture toughness indicated that it will perform well. The low-carbon 9Ni-4Co steel had a relatively high fracture toughness, which indicates that it will also be resistant to stress-corrosion cracking.

Recent Maraging Steel Developments
by R. J. Raudebaugh and B. W. Schaaf, International Nickel Company, Inc.

With the thought in mind that the 18 per cent nickel type of maraging steel might have potentialities for deep-diving-submarine hull plate, Inco submitted, from the first arc-furnace melt produced, some material to NRL for explosion-bulge tests. The particular steel was a little low in titanium (0.35 per cent whereas the aim was 0.5 per cent) and reached only 235,000-psi yield strength after the standard annealing and aging treatment. The plate which had been straightaway rolled had a Charpy V-notch value of 20 ft-lb. It has been the Navy's experience that a Charpy V-notch shelf value of at least 50 ft-lb is needed for satisfactory performance in the explosion-bulge tests. Thus, it was not surprising to find that this first lot of material did not perform acceptably.

Accordingly, a program has been undertaken by Inco to develop a maraging steel which will show a Charpy V-notch value of at least 50 ft-lb at yield strengths in the range of 150,000 to 180,000 psi. All test material was to be provided to NRL in the form of cross rolled 1-inch-thick plate, from some 1000 to 2000 heats, air induction-melted, with and without vacuum remelting.

One approach which was taken to develop the material was to produce alloys of the 18 per cent nickel type but having lower hardener content than the normal 250,000 psi alloy. The aim analysis was 17 to 19 Ni, 8 to 9 Co, 2.5 Mo, 0.1 to 0.2 Ti, and 0.05 to 0.15 Al. The specific composition of one such heat supplied to NRL was 18.04 Ni, 8.7 Co, 2.04Mo, 0.13 Ti, and 0.053 Al. This material attained a yield strength of 160,000 psi and a Charpy V-notch value of 90 ft-lb on being annealed at 1500 F for 1 hour and aged at 900 F for 3 hours. This alloy had been consumable-electrode vacuum-arc remelted.

The other approach being used by Inco to arrive at a hull plate alloy is to omit cobalt from the composition. Inco considers it advantageous to use cobalt, together with molybdenum, in alloys designed to reach yield strengths above 200,000 psi by the standard heat-treating schedule; however, cobalt may not be needed in alloys designed to have less than 200,000-psi yield strength. Combinations under study include: 10Ni, 5Cr, 3Mo, 0.1 to 0.2 Ti, and 0.2 to 0.3 Al; and 12 Ni, with 3 and 5 Cr, 3 Mo, 0.1 to 0.2 Ti, with 0.05 to 0.15 Al and 0.2 to 0.3 Al. One alloy containing 12.21 Ni, 3.17 Mo, 4.98 Cr, 0.18 Ti and 0.22 Al reached a yield strength of 162,000 psi with 70 ft-lb Charpy V-notch value for transverse specimens with a through-the-thickness notch. Thus, with each approach alloys can be developed having a minimum yield strength of 160,000 psi and a Charpy V-notch value of above 50 ft-lb.

As a further development, it was reported that General Electric has been successful in nitriding the maraging steels. Case hardnesses of R_c 66 to 67 have been obtained. Cases of such hardness should have improved wear resistance.

In another study, the effect of long-time holding at 600 and 700 F on the properties of maraging steels is being investigated. The steels range from the 18Ni(150) to the 18Ni(300) grade. They are being studied as aged, and the holding times extend to 1000 hours. Some results were reported. For example, it was found that the Charpy V-notch value for an 18Ni(250) grade steel changed from 18 ft-lb to 16 ft-lb after 1000 hours at 600 F, and from 18 ft-lb to 12.6 ft-lb after 1000 hours at 700 F. The corresponding changes in yield strength were from 269,000 to 282,000 psi at 600 F and from 269,000 to 288,000 psi at 700 F.

In addition, Inco is involved in considerable work on welding of maraging steels. Filler-wire composition is being investigated as it relates both to the grade of 18 per cent nickel maraging steel and to the welding process. Compositions of current interest for steels of 200,000 psi yield strength or higher are as follows:

Grade of Steel	Welding Process	Composition, per cent				
		Ni	Co	Mo	Ti	Al
200	TIG (plate)	18	6	3.4	0.50	0.20
	MIG (plate)	18	1	3.5	0.45	0.10
	Short arc	18	1	3.5	0.33	0.15
	Coated	18	0	3.6	2.25	0.18
250	TIG (sheet)	18	9	4.9	0.55	0.20
	TIG, MIG, short arc (plate)	18	8	4.5	0.50	0.20
	Coated (plate)	18	8	4.5	2.20	0.20
300	TIG (sheet)	17.4	11.5	6.1	0.70	0.20

In weldments made with 1/2-inch 18Ni(200) plate, using the above filler metals, yield strengths averaging 180,000 psi and elongations averaging 5.7 per cent have been obtained with the TIG process. The corresponding values for the MIG process are 191,000 psi and 8.0 per cent, for the short-arc process the figures are 183,000 psi and 9.5 per cent, while coated stick-electrode welding has produced joints with 186,000 psi yield strength and 11.0 per cent elongation.

TIG weldments have been made in the 18Ni(250) grade of steel in the form of 0.062-inch-thick sheet which had yield strengths averaging 245,000 psi with a K_c value of 191,000 psi $\sqrt{in.}$ Weldments in 1/2-inch-thick plate from the 18Ni(250) steel made by the MIG process showed yield strengths of 220,000 psi and elongations averaging 7 per cent; when short-arc welded, the values were 228,000 psi and 4 per cent. Coated stick-electrode welding produced joints with 225,000-psi yield strength and 6 per cent elongation.

A cold pass technique was investigated for welding 0.062-inch-thick 18Ni(300) steel sheet with the TIG process. The weldment showed yield strengths averaging 276,000 psi with K_c values in the order of 97,000 psi $\sqrt{in.}$ With a modified filler wire for welding the 12-5-3 type of maraging steel under study for hull plate, joints are obtained having a Charpy V-notch value of 60 ft-lb at a yield strength of 160,000 psi, 50 ft-lb at a yield strength of 165,000 psi, and 40 ft-lb at a yield strength of 170,000 psi. Joint efficiencies of 90 per cent are reported.

Evaluation of High-Strength Light-Weight Laminated Pressure Vessels of Lap-Joint Construction
by G. Citrin, Republic Aviation Corporation

The purpose of this effort was to evaluate the basic feasibility and the confidence level achievable by using the overlapping cylinder design for the construction of pressure vessels. Three thicknesses of material, 0.021, 0.038, and 0.062 inch, were chosen for the fabrication of vessels having total wall thicknesses of 0.042, 0.075, and 0.125 inch, respectively. The vessels were approximately 24 inches in diameter and ranged from 3-1/2 to 6 feet long.

The studies were conducted on three heats from two different sources. One heat was of the 18Ni(250) grade and the other two were 18Ni(300) steels. An investigation was made to determine the optimum starting condition for the metal. Studies were also made of mechanical properties, welding characteristics, the influence of cold work, sizing behavior, spring back, tensile properties of weldments, control of weld bead contour, and the preparation of the surface for application of the adhesive.

Fabrication of the maraging-steel rings so that the diametric interference of the metal parts and adhesive ranged from line to line fit to a maximum of 0.008-inch diametric interference. The adhesive was fixed to the inner rings by vacuum bag molding at 150 F for 1 hour. The outer rings and headers were forced over the inner rings (by a mechanically applied driving force) at room temperature. The slight diametric interference was overcome primarily by elastic deformation in the uncured adhesive. The assembly, after being vacuum bagged and autoclave molded at 325 to 350 F for 1 hour, was cured under heat and at a pressure depending on the thickness of the maraging sheet-metal rings (0.021 inch rings, 45 psi; 0.038 inch rings, 80 psi; 0.062 inch rings, 110 psi). As a last step, the vessel was coated internally with a neoprene rubber compound as a sealant and baked at 150 F for 3 hours.

To date, six pressure vessels have been assembled and pressure tested to failure. Three vessels were fabricated of 0.021-inch-thick material, two vessels of 0.038-inch-thick material, and one vessel of 0.062-inch gage maraging steel.

Of the six vessels tested, four failed in the metal rings and two failed in the adhesive. Both adhesive failures were attributed to the use of work-horse reuseable closures. The design of these closures requires the skirt section to be substantially thicker than the maraging steel rings that are bonded to the skirt and make up the cylindrical portion of the vessel. The resultant stiffness in the skirt portion prevents uniform curing pressure if there is less than optimum mating of the faying surfaces.

Among the instances where failure began in the metal, one occurred in parent metal at a stress level above the uniaxial strength, another started at a flaw in the parent metal, another failed in a weld, and the fourth failed in parent metal, showing a gratifying 12 per cent biaxial gain.

Maraging Steel in Elevated Temperature Airframe Design
by J. A. May, North American Aviation, Inc., Los Angeles

A program on the 18Ni(300) grade of maraging steel is in progress at North American Aviation, Inc. (Los Angeles Division). The primary purpose of the program is to develop information for the design of large structural fittings for airframes which will be exposed to temperatures up to 650 F.

The information presented includes longitudinal and transverse notched and unnotched tensile strength, compressive yield strength, shear ultimate strength, bearing ultimate and yield strength for $e/D = 1.5$ and 2.0, axial-loaded fatigue S-N curves for smooth and notched bars, and 650 F creep data. Data on effects of strain rate, and on effects of long-time exposure on tensile properties are also included. Limited formability and weld data are presented.

On the basis of data obtained to date, the 18 per cent nickel maraging steels appear to be suitable for airframe structural applications subject to temperatures up to 650 F.

The NAA program on the 18Ni(300) maraging steel involves an evaluation of bar, sheet, and plate stock. Material for the program was 3-1/2 by 7-inch bar stock from two heats, 0.063-inch sheet stock from three heats, and 0.250- and 0.500-inch plate stock from two heats. The sheet and plate stock were used primarily for formability, welding, and chemical-treatment tests; however, a mechanical-property spot check on the sheet and plate showed good agreement with the properties developed in the bar stock. All material was purchased as solution-annealed consumable-electrode vacuum-arc-remelted stock. The best treatment for the bar stock was found to be 3 hours at 900 F, while 6 hours at this temperature was found to be optimum for the sheet and plate.

Mechanical properties for the bar stock both at room temperature and 650 F were presented. Approximately 85 per cent of the room-temperature strength properties was retained at 650 F.

Considerable variation in bearing yield strength led to examination of the microstructure around the pin holes in both high- and low-bearing-yield coupons; a disturbed surface structure in the high-bearing-yield specimen was observed. The disturbed layer was less than 0.001 inch deep, which

made hardness tests impractical; however, by following the change in width of polishing scratches it appeared that the disturbed surface layer was harder than the underlying material. Fabrication sequence for the bearing coupons involved machining to finish dimensions, then age hardening. Apparently, sufficient work hardening occurred in drilling the annealed material that upon age hardening the shallow surface layer developed enough additional strength in the hole to influence the yield strength, but not the ultimate strength. An examination of the microstructure of other test coupons produced primarily by milling or lathe operations showed no evidence of a disturbed surface layer. However, it is expected that careless machining in mill or lathe cutting would create a work hardened surface condition similar to that caused in drilling, particularly if dull cutting tools were used for making shallow finish machine cuts.

A similar experience was encountered in the preliminary testing of a (250)-grade maraging steel. In this case, fabrication of notch tensile coupons required final machining (single-point lathe cutting) of the notch after the test coupons had been age hardened. A comparison of test results on "machined and stress relieved" and "as machined" notch coupons from the (250)-grade steel showed that stress relieving resulted in significantly higher properties. Stress-relief treatment used in the tests was 2 hours at 850 F. (It was noted that smooth tensile coupons subjected to the same stress-relief cycle were no stronger or more ductile than tensile coupons not stress relieved; therefore, the increase in notch strength was not a case of continued aging.) On the basis of these experiences, the author considered that deformation and residual stresses developed in machining may be a factor explaining inconsistencies in properties sometimes noted by other investigators.

The grain size of the billet stock was observed to vary from a surface grain size of about 2 to about 6 at the center of the bar. The change in grain size from surface to center of the bar had little effect on the tensile ultimate and yield strength at the various locations within the bar. However, ductility was greatly affected. In the large-grain structure (0.4 inch from the surface) no measurable elongation was recorded in a test coupon with a 2-inch gage length, and very localized necking produced only 19.6 per cent reduction in area. As the grains became finer toward the center of the bar, elongation and reduction in area became progressively better. At the center of the bar, where the grain size appeared to be about number 5 or 6, elongation reached 6.3 per cent and reduction in area reached 40.3 per cent.

To determine if the direction of raw-stock grain flow would be a significant factor (as it is in many metallic materials) in load-carrying capabilities of "hog-out" parts, notched and unnotched tensile and fatigue coupons taken both longitudinal to and transverse to the raw-stock grain flow of each heat of bar stock were tested. As expected, the transverse tensile properties exhibited a notable, but acceptable, loss when compared with longitudinal tensile properties. The relatively low notch-to-unnotch tensile-strength ratio exhibited by both heats of material came as a surprise (1.02 to 1.20). Other investigators have reported notch-to-unnotch ratios of 1.3 and higher for notch factors more severe than the 3.3 used here. Since both longitudinal and transverse coupons from each heat were processed in the same heat-treat load, processing variables should not be a factor in these tests. To date, the only apparent fact which the authors considered might explain the low tensile notch-to-unnotch ratio on the two heats of material was a comparatively large austenitic grain size.

At low-cycle lives the fatigue characteristics of the two heats of material were similar to the tensile data: transverse data for both notch and unnotch coupons were lower than the longitudinal data. However, at about 200,000 cycles, longitudinal and transverse data converged, for a greater number of cycles, grain direction appeared to have no effect on fatigue properties. The convergence of longitudinal and transverse data occurred in notched coupons at both room temperature and 650 F, but only at room temperature on unnotched coupons.

Effects of long-time heating on 18 per cent nickel maraging steel were investigated by exposing tensile coupons from each heat of bar stock to temperatures of 500 F, 650 F, or 800 F for periods up to 1000 hours. No apparent change in properties occurred with prolonged heating at 500 F. When compared with unheated coupons, prolonged exposure to temperatures at both 650 F and 800 F caused an increase in tensile strength and a loss in ductility, the highest temperature causing the greatest change. However, there was a suggestion of overaging after 200 hours at 800 F.

To determine if the maraging steels exhibited the usual trend of high strength at higher strain rates, longitudinal and transverse coupons from one of the heats were tested at rates of 0.005, 0.05, and 0.12 inch per inch per minute. Both the longitudinal and the transverse yield and ultimate strengths were found to be quite insensitive to strain rate. Also, the ductility values of the steel exhibited no definite trend with increase in strain rate. Elongation in both the longitudinal and transverse direction was almost constant; less than 1 per cent variation existed between the highest and lowest values.

Creep tests were made on each heat of bar stock at 650 F and 800 F. The goal was to develop curves at 10 hours, 100 hours, 500 hours, and 1000 hours for 0.1, 0.2, 0.5, and 1.0 per cent permanent elongation at each temperature. However, it soon became apparent that very high loads (75 to 90 per cent of the elevated ultimate strength) would be required to produce any appreciable creep at 650 F. Therefore, test conditions at 650 F were limited to determining permanent elongations of 0.05, 0.1, and 0.2 per cent. After completion of the creep test, the test coupons were tensile tested at room temperature to determine if exposure to temperature under load caused any unusual changes. Results of room-temperature tensile tests after completion of the 650 F creep test showed that a continuation of the aging process was occurring to offset the effects of temperature. The data also indicated that load at temperature does not accelerate the aging process. At 800 F the original requirements of the creep test were achieved. If the 18 per cent nickel maraging steel is to be used at 800 F for prolonged periods, creep must be taken into account: the normal 66 per cent design limit load will cause 0.5 per cent creep in about 75 hours.

Since 18 per cent nickel maraging steels are martensitic alloys, chemical cleaning and plating were evaluated for the possibility of creating hydrogen-embrittlement problems. Generally, cleaning of structural shapes would be done by grit blasting; however, past experience with high-strength materials has shown that chemical cleaning is desirable in some cases where metal removal is critical, or for some internal cavities where grit blasting is not practical. Platings are required on the maraging steels to prevent corrosion. The chemical cleaning treatment investigated consisted of an

alkaline soak followed by rinsing in an inhibited acid bath. To date, two significant facts have been revealed in this evaluation; (1) embrittlement does occur but can be relieved by adequate baking after plating and (2) surface cleanliness will be a major problem in achieving adherent electroplated, and possibly vacuum-deposited, coatings. Complete success in plating with nickel-zinc alloy has been achieved. Removal of embrittlement in plated specimens was accomplished by a 23-hour bake at 375 F. Sustained-load tests on notched specimens (K_t = 3.5) from both heats of material produced no failures in 3000 hours when loaded to 90 per cent of the ultimate strength. Only partial success has been achieved in the remaining sections of this evaluation. Chromium plating has been difficult from the standpoint of adhesion. Most of the common surface cleaning methods, such as grit blasting, alkaline cleaning, and anodic cleaning did not provide a suitable surface for uniform plating adhesion. Chemical cleaning by the two-step alkaline soak method has only been partially successful: a soot generated in the alkaline bath is not completely removed in the inhibited acid bath. Phosphate treatment has been impossible.

Welding of 18 Per Cent Ni-Co-Mo Maraging Alloys
by R. E. Travis and C. M. Adams, Jr.
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Five different heats of maraging steel with tensile strengths of 250,000 to 325,000 psi were investigated. The 250,000 psi material investigated was 0.080, 0.125, and 1/2 inch thick. The 300,000 psi material was 0.068, 0.080, and 0.200-inch-thick sheet and 1/2-inch bar stock.

The two types of specimens employed in evaluating tensile properties were a standard tensile and a slotted tensile designed to produce biaxial loading.

The yield strengths (0.2 per cent offset) of all materials tested were within 5 per cent of the uniaxial ultimate tensile strength. A comparison of TIG and short-arc weldments in thin nominal 250,000 psi material indicated that the TIG weldments were slightly superior. However, weldments in 1/2-inch-thick plate indicated MIG to be slightly superior to TIG with respect to yield strength and uniaxial ultimate tensile strength. A substantial drop in elongation (2-inch gage length) from approximately 9 per cent for base plate to about 2.5 per cent for weldments was observed. Joint efficiencies on both uniaxial and biaxial welded specimens which were solution annealed and aged after welding averaged 96 per cent.

The joint efficiencies of both TIG and electron-beam weldments which were aged directly after welding without any solution anneal averaged 88 per cent. Indications were that solution annealing and aging subsequent to welding produces higher weld-joint efficiencies than does direct aging after welding.

In all cases, biaxial loading increased the ultimate tensile strength of the material being tested. In all of the uniaxial as well as biaxial tensile specimens, fracture took place within the weld metal or immediate heat-affected zone, so that the magnitudes of biaxial strengthening were characteristic of the weld. A comparison of the results obtained with the uniaxial and biaxial

specimens of the nominal 250,000 psi material showed a strength increase of approximately 10 per cent. The strength increase of the nominal 300,000 psi material was the order of 15 per cent.

Peak temperatures associated with the edges of the darkly etching region of the heat-affected zone have been identified and measured. The inner edge of the first dark-etching region adjacent to the weld metal experiences a peak temperature of 2038 F, the outer edge 1710 F, and the second heat-affected zone 1387 F.

Fracture Toughness Critique
by W. F. Payne, Air Systems Division, USAF

The selection of the 18 per cent nickel maraging steels for large boosters of the 156-inch and 260-inch varieties was briefly discussed. The commentary centered on studies made by Boeing and by Aerojet-General on case weight and on the cost of the case for vehicles to boost payloads in the order of 500,000 lb. The materials considered were low-alloy hardenable steels and maraging steels, with ultimate tensile strengths ranging from 150,000 to 300,000 psi. The general conclusion of these studies is that case weight can be expected to be somewhat less with the maraging steels than with the other steels considered. Also, the results of the studies indicated that over-all costs are quite insensitive to the basic cost of the steel. Therefore, the choice of the construction material rests on the technical factors. Prominent among these factors are availability of the desired mill forms, capability to be formed and fabricated, weldability, and mechanical and physical properties, including fracture toughness.

The 18 per cent nickel maraging steels are favored because the data thus far collected on them indicate that they have a fracture toughness which is considerably superior to that of other candidate steels. The thicknesses required in the design of large boosters place a particular burden on the fracture toughness of the material, and a completely reliable structure will need a steel having at least as good fracture strength as the 18 per cent nickel maraging steels. The critical nature of the situation comes into sharp focus when the fracture toughness of weldments is being considered; here, the probability that intolerable flaws are present increases, and the tendency is for the fracture toughness to decrease. Another item of concern is the short transverse direction of plate, bar, and forgings, which becomes important under conditions of triaxial loading. The fracture strength in this direction is much less than in the other material directions. Consideration of such items as these indicates the advisability of using grades of 18 per cent nickel maraging steel that do not attain yield strengths over 250,000 psi. In fact, it may well be wise to aim for yield strengths in the range of 225,000 to 235,000 psi in order to have acceptable fracture strength.

Fracture toughness is not only a dominating materials selection criterion but it is also a vitally important factor in design. Therefore, it is important to examine carefully the measurement of this characteristic. The author commented on the various methods of measuring and calculating fracture toughness, expressing preference for the use of plane-strain fracture-toughness criteria such as K_{Ic} values. In this connection, he emphasized the importance

of establishing experimental conditions that produce plane strain. For surface- or part-through-cracked tension specimens he noted that crack depth should be less than half the thickness and that, to properly describe the test, both the crack depth and the crack length should be reported.

A schematic diagram was presented illustrating the relationship between strength and plane-strain fracture toughness which seems to prevail among known constructional steels. The limiting boundary of material capability was indicated as a line depicting a tendency for strength and fracture toughness to be related inversely to each other. This line is intersected by a strength vs. plane-strain fracture toughness parameter line separating fracture-producing conditions from those that do not produce fracture, all other things equal. The useful high-strength structural alloys are those with strengths vs. fracture toughness properties just inside the materials-capability boundary and just under the fracture-no fracture line. In this concept, the function of alloy development is to extend outward the capability boundary line and thus make possible higher values of both fracture toughness and strength.

LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963
166	Literature Survey on the Effect of Sonic and Ultrasonic Vibrations in Controlling Grain Size During Solidification of Steel Ingots and Weldments, May 15, 1963
167	Notes on Large-Size Furnaces for Heat Treating Metal Assemblies, May 24, 1963 (A Revision of DMIC Memo 63)
168	Some Observations on the Arc Melting of Tungsten, May 31, 1963
169	Weldability Studies of Three Commercial Columbium-Base Alloys, June 17, 1963
170	Creep of Columbium Alloys, June 24, 1963
171	A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys, July 15, 1963
172	Production Problems Associated with Coating Refractory Metal Hardware for Aerospace Vehicles, July 26, 1963
173	Reactivity of Titanium with Gaseous N_2O_4 Under Conditions of Tensile Rupture, August 1, 1963
174	Some Design Aspects of Fracture in Flat Sheet Specimens and Cylindrical Pressure Vessels, August 9, 1963
175	Consideration of Steels with Over 150,000 psi Yield Strength for Deep-Submergence Hulls, August 16, 1963
176	Preparation and Properties of Fiber-Reinforced Structural Materials, August 22, 1963
177	Designations of Alloys for Aircraft and Missiles, September 4, 1963
178	Some Observations on the Distribution of Stress in the Vicinity of a Crack in the Center of a Plate, September 18, 1963
179	Short-Time Tensile Properties of the Co-20Cr-15W-10Ni Cobalt-Base Alloy, September 27, 1963
180	The Problem of Hydrogen in Steel, October 1, 1963